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and the

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ARGILLIC ALTERATION AND ORE DEPOSITS

GEORGE M. SCHWARTZ

ABSTRACT

The prominence of clay minerals in the hydrothermally altered rocks of many mineral deposits has been emphasized in recent years. The presence of clay minerals of hydrothermal origin has long been recognized but for obscure reasons not much importance had been attributed to them. It has now been shown that most of the minerals belonging to the clay groups (kaolin, montmorillonite and hydromica groups) occur abundantly in many hydrothermally altered rocks. In general the clay minerals form during the early stage, or advancing front of the alteration and are commonly converted to sericite as the process continues.

The detailed paragenesis of clay minerals in hydrothermally altered rocks is imperfectly known and needs much work for its clarification.

INTRODUCTION

IN recent years much emphasis has been placed on the clay minerals occurring in the hydrothermally altered rocks with which many ore deposits are associated. Most occurrences are in ores of mesothermal and epithermal classes but abundant kaolinite also occurs in the tin-bearing greisens of Cornwall, England and elsewhere. The hydrothermal and pneumotolytic origin of kaolinite was recognized as long ago as 1819 when Martini noted that kaolin deposits at Aue in Germany occurred at the top of a granite stock between converging hematitic veins.

Over the years many workers have described clay minerals as hydrothermal products but as a rule little emphasis was placed on that fact. Lindgren's 1915 paper (14) stressing the role of meteoric waters in the origin of kaolin may have had a restraining influence on those who recognized a hydrothermal origin but doubtless considered the occurrence exceptional.

Lindgren (14) noted that Rösler (22) held in 1908 that kaolin is not formed by weathering but only by the action of thermal waters or pneumatolytic processes. Rösler (24) had also published an extensive paper in 1902 which emphasized the hydrothermal origin of kaolin. In a discussion of Rösler's 1902 paper Weinschenk (33) gave a long list of primary ore deposits

that contained hydrothermal kaolin. It should be noted that at the same time Dammer argued for the supergene origin of kaolin.

In view of the literature with which he was familiar, it is somewhat surprising that Lindgren (14) came out so strongly for the proposition that kaolin was normally a product of supergene solutions.

It is evident that the modern recognition of the importance of hydrothermal clay minerals in ore deposits developed gradually. Burbank's (1) description of the Bonanza district in 1932, Graton and Bowditch's emphasis on clay minerals of hydrothermal origin at Cerro de Pasco, and Lovering's 1941 paper on the tungsten ores of Boulder County, Colorado (15) led to the recent emphasis on hydrothermal argillic alteration in many ore-bearing districts. Since 1941 a number of papers by Sales and Meyer, Lovering, Peterson, Kerr, Leroy, Schwartz and others have shown that clay minerals of hydrothermal origin are surprisingly abundant, particularly in and near copper deposits.

It seems clear that recognition of the importance of clay minerals as hydrothermal products in the past 15 years has been greatly aided by: (1) modern methods of mineralogical research applicable to the fine grained clay minerals; (2) a better understanding of the genesis of ore deposits; (3) better opportunities for observation furnished by the extensive mining in recent years (4) the much more detailed geological work now carried out in most ore-bearing districts. Possibly also there has been less emphasis on preconceived ideas. In any event we seem to be arriving at a much better appreciation of the true role of argillic alteration in many ore-bearing districts.

REVIEW OF EARLY WORK

It would be difficult, if not impossible to determine with any certainty the first individual to recognize that clay (kaolin) could be formed by the effect of hydrothermal solutions and gases on feldspar and other aluminous minerals. The earliest reference the writer has found is a statement by Stutzer (31) that a manuscript by Carl Martini dated 1819 shows a diagram of the kaolin deposit at Aue, Germany in which the top of a granite stock is kaolinized between iron-bearing veins that converge upward. It seems clear that Martini believed that the alteration to kaolin was caused by the vein forming solutions or gases. Stutzer (31) investigated the same deposits and concluded that the kaolin was an extreme end product of feldspar and that kaolinization could no longer be considered a product of weathering but resulted from post-volcanic processes.

In describing the ores of Custer County, Colorado, S. F. Emmons (7) in 1896 described kaolin closely associated with pyrite crystals in highly altered material within the area of ore deposition. The feldspar crystals were thoroughly kaolinized and the description leaves little doubt that Emmons believed that the alteration to kaolin was a part of the ore-forming process.

In 1900 Weed described the alteration at Boulder Hot Springs in Montana. Petrographic notes furnished by Waldemar Lindgren stated that in altered granite much larger quantities of kaolinite than sericite are present. The

kaolinite occurred as minute irregular scales that had replaced feldspar. Grains of quartz were noted in various stages of kaolinization.

In the Silverton district of Colorado, Ransome (19) in 1901 referred to kaolinite as an original constituent of the ores in the Red Mountain area. The kaolin occurred as firm compact masses intimately associated with pyrite, the latter traversing the kaolin as anastomosing veinlets so that the hydrothermal alteration seemed evident. In the Zuni mine kaolinite is also associated with pyrite and enargite.

In the Tomboy and Camp Bird Mines kaolinite is associated with the gold-bearing quartz and in the Tomboy mine it is mixed with sericite. Thus Ransome clearly recognized the hydrothermal origin of kaolinite in connection with mineral veins. To emphasize the epigenetic nature Ransome stated that kaolinite accompanied the ores to the depth of 1,300 feet, which was the maximum depth of mining in the district.

Ransome's well-known ability as an observer is illustrated by the fact that he repeatedly recognized kaolinite as a hydrothermal mineral. At Goldfield (21) he described kaolinite associated with alunite in altered rocks near the ore bodies. Mineral composition calculated from an analysis of dacite showed 24 percent kaolinite which occurred intercrystallized with quartz, alunite and pyrite. While recognizing kaolinite as an alteration product formed during weathering, Ransome concluded that the bulk of the kaolinite at Goldfield was primary, i.e., hypogene.

In the Ray and Miami districts Ransome (24) described kaolinite associated with sericite and quartz in altered granite where it could not have formed by weathering, for example, beneath an orebody in unenriched metallized porphyry or protore. It is also stated that where sericite and kaolinite occur together, the sericite is younger and replaces the kaolinite.

In spite of the above examples in his paper on criteria of downward sulphide enrichment Ransome (22) quoted Lindgren to the effect that kaolin occurs only in the oxidized zone and in the zone of sulphide enrichment. In commenting on that statement Ransome noted the occurrence of kaolin at Silverton and Goldfield but ended by saying, ". . . this exceptional occurrence does not conflict seriously with the view that the mineral is rarely formed except in the zone of enrichment."

Another example of the recognition of hydrothermal kaolinite is that reported by Spurr and Garrey (29) for the Georgetown, Colorado district published in 1908. There kaolinite is said to be contemporaneous with quartz, barite, galena, blende, and polybasite.

Butler (2) in a description of the San Francisco district, Utah states that kaolinite is abundant in the altered rocks associated with the ores of the Carbonate mine where it apparently resulted from the action of solutions that produced the ore deposits. Later Butler and co-workers (3) stated that kaolin was a late mineral of the ore-forming process in the Keweenaw district of Michigan.

Day and Allen (4) in 1925 concluded from their study of hot springs in the Lassen Peak area that kaolin minerals are products of hot or cold acid waters in contrast to sericite which presumably formed from alkaline solutions.

One of the more detailed accounts of the hydrothermal origin of the kaolin minerals is given by Burbank (1) in his report on the Bonanza district where Ransome in 1901 had recognized the hydrothermal origin of clay as noted above. Burbank concluded that kaolin was a by-product of silicification of volcanic rocks and, therefore, was of hydrothermal origin. Fine-grained clay minerals are associated with quartz, barite, and sericite. The clay minerals replace feldspar phenocrysts and fill cavities in quartz. At Red Mountain it is stated that the addition of silica and the formation of kaolinite, generally without sericite, constitutes the characteristic alteration. An association of kaolin with alunite, diaspore and zunyite as a by-product of silicification is said to be a result of solutions of either lower temperature or lower acidity.

The work of the past 20 years is too well known to warrant repetition of the details, but the typical mineral association and general paragenesis are summarized for rapid comparison of some of the more detailed studies of hydrothermal alteration where clay minerals are involved.

Cerro de Pasco (10)

Feeble phase—chlorite, calcite, epidote, quartz, sericite.

Moderate phase—Sericite, pyrite, quartz.

Intense phase—Quartz, pyrite, kaolin (dickite), zunite, alunite, zoisite.

The more intense phase is adjacent to the copper ore

Boulder County, Colorado (15, 16)

Argillized zone.

Outer sub-zone. Allophane, montmorillonite (?), hydrous mica, sericite

Transition sub-zone. Beidellite abundant.

Inner sub-zone. Dickite, beidellite, halloysite etc.

Inner zone.

Sericite, hydrous mica, dickite, quartz, adularia.

Castle Dome, Arizona (17, 18)

Propylitic (marginal) phase—sericite, epidote, clinozoisite, chlorite, calcite, leucoxene.

Argillic phase—hydrous mica, montmorillonite-type clay (beidellite?) kaolinite, leucoxene, allophane.

Quartz-sericite phase—sericite, quartz, kaolinite, pyrite, etc.

Morenci, Arizona (27)

Argillic phase—allophane, halloysite, hydrous mica, kaolinite, beidellite, chlorite.

Sericite phase—sericite, quartz, kaolinite, pyrite, etc.

San Manuel, Arizona (29)

Type 1. Kaolinite, alunite, plus lesser quartz, sericite, hydrous mica, halloysite, beidellite, allophane, leucoxene, chlorite.

Type 2. Hydrous mica, alunite, kaolinite, chlorite, sericite allophane and rutile.

Type 3. Sericite, quartz, pyrite, chalcopyrite, plus lesser kaolinite, hydrous mica, beidellite, rutile, leucoxene.

Type 4. Secondary biotite, hydrobiotite, chlorite, hydrous mica, epidote, zoisite, sericite, rutile, leucoxene, kaolinite, halloysite, allophane.

Ely, Nevada (*27*)

Dark phase: Biotite, hydrobiotite, chlorite, sericite, hydrous mica, potash clay, kaolinite, allophane.

Light-phase: Quartz-orthoclase, sericite, biotite, chlorite, sericite, kaolinite.

Ray and Miami, Arizona (*27*)

Early phase: kaolinite, hydrous mica, halloysite, allophane, chlorite.

Later phase: sericite, quartz, pyrite, chalcopyrite.

Bisbee, Arizona (*27*)

Quartz, sericite, hydromica, kaolinite, allophane, alunite, chlorite, calcite, rutile, leucoxene, zoisite, halloysite, pyrite.

Butte, Montana (*26*)

Argillized zone.

Montmorillonite subzone—montmorillonite-type clay, nontronite-type clay, chlorite, carbonate, epidote, allophane.

Kaolinite subzone—kaolinite, biotite plus remnants of minerals of the montmorillonite subzone.

Sericite zone.

Sericite, quartz, pyrite, dickite, alunite.

Santa Rita, (Chino) New Mexico (*11, 13*)

Stage 1. Slightly altered, chlorite, sericite, etc.

Stage 2. Chlorite, secondary biotite, montmorillonite, hydromica, quartz, sericite, kaolinite, alunite.

Stage 3. Sericite, hydromica, kaolinite, quartz, alunite, pyrite, limonite.

Stage 4. Quartz, sericite, rutile, alunite, kaolinite.

Silver Bell, Arizona

Kerr recognized 4 stages but these vary with the original rocks. They are generalized by the writer as follows:

Stage 1. Essentially unaltered.

Stage 2. Chlorite (abundant), calcite, traces of kaolinite, hydromica, sericite, leucoxene, montmorillonite.

Stage 3. Brown mica, hydromica, kaolinite, sericite, secondary quartz, orthoclase, main copper sulphide stage.

Stage 4. Sericite, hydromica, kaolinite, orthoclase but largely alteration is to quartz and sericite in the most intense stage.

Bingham, Utah (*30*)

Stage 1. Illite (hydromica), kaolinite.

Stage 2. Biotite, sericite.

Stage 3. Biotite, chlorite.

Stage 4. Quartz, sericite.

Stage 5, 6 & 7. Involve deposition of quartz, sulphides, sericite and allophane in fractures.

DISCUSSION

It is noteworthy that about 20 years ago the many varieties of clay minerals which became more easily recognized by X-ray methods made their appearance in the reports on studies of hydrothermal alteration and the general term kaolin tended to disappear from such descriptions.

The tabulations emphasize the fact that many minerals occur in hydrothermally altered rocks, and although there is some similarity of associations there are also marked differences from district to district.

The general order in which the minerals tend to form is, by no means consistent from district to district but here too, there are differences as well as similarities. It is not to be expected that temperature, pressure, and composition would be entirely similar in widely spread districts, nor, indeed, is it probable that different workers would always recognize the same sequence in a given district because, at best, criteria for sequence are not always definite or easy to recognize. The rocks through which the solutions move have a profound modifying effect on the solutions as has been so effectively shown by Sales and Meyer (26). The variation in alteration of porphyry by solutions that pass through limestone in contrast to those limited to the porphyry was previously noted by the writer in the Bisbee district (27).

In general, the detailed studies published during the past 15 years suggest that the common sequence is a distinctly argillic alteration, either early or in zones away from the vein as at Butte, succeeded by sericitic alteration or deposition accompanied by pyrite and copper sulphides. At places a chloritic or propylitic alteration may extend beyond the argillic alteration but this does not appear to be consistent from district to district.

At Butte where well defined veins aid in determining both space and time relations, Sales and Meyer (26) have argued convincingly for the simultaneous growth of the argillic and sericitic zones but the sericitic zone did encroach on the argillic zone as the vein grew so that, in a sense, the sericite is later than the clay minerals at any one point. Where a very large mass of rock has been argillized, as at Morenci, and is cut by a complicated network of veinlets of sericite it is more difficult to visualize the argillic alteration as a wave which advanced ahead of the simultaneous sericite alteration. There it seems plausible that the solutions which partially sericitized the rock followed the solutions which thoroughly altered the original porphyry to a rock in which the principal minerals other than quartz are: kaolinite, halloysite, allophane, etc.

As would be expected the hydrothermal clay minerals form mainly by the alteration of feldspar. Plagioclase is particularly susceptible to hydrothermal attack including argillization but orthoclase is resistant although if the process is active enough it does alter more or less completely. Biotite alters to a variety of minerals including locally such clay minerals as hydromica, nontronite and kaolinite. Hornblende also occurs partly altered to nontronite, kaolinite, dickite, etc. Kerr (1950, p. 345) notes that epidote alteration is obliterated by a later argillic alteration.

Quartz is generally resistant to most kinds of alteration but it has been noted by several investigators that in cases of severe argillic alteration it is attacked around the periphery of large grains and Lovering (16, p. 37) in-

dicates that the groundmass quartz and orthoclase of a porphyry at Tintic is changed to clay.

When later alteration attacks argillized rocks sericite is readily formed at the expense of the clay minerals.

It would be premature to try to draw any firm conclusions as to the exact role of the clay minerals in hydrothermal alteration but it is evident that it is a very important one. Many more detailed studies are needed and eventually some unbiased review should be undertaken to determine if any general pattern does in fact exist.

An important problem is the distinction between clay minerals of hydrothermal origin and those formed by weathering. The proof of an abundance of clay minerals in hydrothermally altered and metallized rocks rests firmly on the fact that this alteration continues far below the zones of oxidation and supergene sulphide enrichment.

Good evidence of the hydrothermal origin is furnished by the mineral associations, particularly minerals commonly of hydrothermal origin, such as sericite in association with pyrite, chalcopyrite, enargite and many other minerals.

If mine openings or drill samples are available from the hypogene zone the problem is not particularly troublesome but when only the zone of weathering, and perhaps of supergene sulphide enrichment, are open to examination a real problem arises in distinguishing between the clay minerals of hypogene and supergene origin.

Thus far such studies as the writer has been able to make, suggest that in deposits where clay minerals and sericite are abundant, weathering does not develop much additional clay, at least not in the relatively arid southwestern United States where observations have been made. Under arid conditions sericite seems to be very stable and does not alter to clay minerals even at the grass roots. A significant fact shown by work done at Morenci in cooperation with Dr. Louis E. Reber, Jr., is that highly sericitic zones do alter to a clay in the textural sense but microscopic and chemical studies show that the principal mineral remains sericite. The writer's explanation is that weathering destroys the bond between the minute sericite grains which thus becomes clay-like, in fact is clay in a textural classification but definitely is sericite mineralogically.

The whole problem of weathering of the hydrothermally altered rocks needs detailed study. It also seems to the writer that the conclusion that kaolinite and other clay minerals are formed abundantly by the sulphuric acid solutions active in supergene enrichment should be reexamined in the light of the abundance of clay minerals in rock altered by hypogene processes.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
March 19, 1956

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THE DIRECTION OF FLOW OF MINERALIZING SOLUTIONS, BLYKLIPPEN MINE, GREENLAND

W. H. GROSS

ABSTRACT

There are at least five methods for determining the direction of flow of mineralizing solutions. It is the purpose of this paper to review these methods briefly, to show how four of them have been applied at the Blyklippen mine, and to discuss their possible value as guides to exploration for ore.

ALTHOUGH an exhaustive search of the literature has not been made, there appear to be only a few cases where geologists have used the direction of flow of mineralizing solutions as a guide in their search for ore. The Blyklippen mine [1] is relatively simple in structure and mineralogy, and therefore it is perhaps a good location to evaluate the various techniques for estimating the direction of flow.

METHODS FOR DETERMINING FLOW DIRECTIONS

Structural Method.—One of the accepted theories of ore formation today is that ore-bearing solutions move through structural channelways in the rocks, and that ore is deposited in favorable environments within the channel system. Theoretically, the direction of flow of solutions can be estimated by making an analysis of the structural patterns around ore bodies. Usually this is difficult to do because of lack of information or because of the structural complexities around the ore. Therefore, when geologists say that ore solutions moved along certain channelways, the direction of flow is presumed oftentimes in quite general terms.

Occasionally the flow direction may be inferred by locating areas of low pressure into which solutions would flow or areas of greater permeability along which solutions would tend to move. Areas of low pressure, for example, might include shrinkage cracks formed by cooling or alteration, tension features such as gash veins, saddle reefs, or the curved parts of fault zones which tend to open during movement (15). The relative permeability might be estimated by noting the intensity of fracturing or the width and development of brecciation and shearing from place to place along a fault zone.

Usually definite conclusions concerning flow direction cannot be reached by knowledge of the structure alone. However, the structure, combined with such features as wallrock alteration, may indicate the general path that the solutions travelled, and this information is often useful in helping to interpret results obtained by other methods.

[1] Published with the permission of V. Brinch of the Northern Mining Co. & J. D. Bateman, chief geologist, Ventures Ltd.

Mineral Zoning.—The zonal theory as advanced in America by Spurr and Emmons assumes that ore solutions come from a magma, and that minerals are deposited with falling temperature as the solutions moved away from the magma source. Field evidence shows that the so-called high temperature minerals of such elements as tungsten and molybdenum occur near the source, and the low temperature minerals of silver and antimony occur far away. Spurr (21) gave the order of deposition away from the intrusive as Mo, W, Ag, Zn, Pb, Hg; Emmons (7) extended this sequence to include 16 minerals.

The difficulty with the zonal theory is that many districts show no apparent zoning. Furthermore, in some mines the zones are reversed and in others they are compressed or telescoped. Although some of these anomalies may be explained by such processes as two ages of mineralization or the rearrangement of the minerals by supergene effects (8), nevertheless, difficulties remain and many geologists are skeptical about the theory.

On the other hand, in some mines it is found that the quantity of certain metals varies with respect to others in accordance with the zonal theory. For example, it is often found that zinc, as compared to lead, increases with the depth in a mine, or gold increases compared to silver, lead to silver, arsenic to copper and so forth. In some cases there is enough information available through a mine to show the relationship of the flow direction to the metal zoning. For example, in the Austinville mine in Virginia, Brown (5) analyzed the changes in the lead-zinc and other ratios, and by assuming that the solutions flowed from areas of high zinc to high lead in accordance with the zonal theory, he built up a picture of the direction of flow of the ore-bearing solutions in the mine.

Crystal Analysis.—One of the methods for determining the flow direction was advanced by Newhouse (17). It depends on observing certain features in crystals found in vugs within the flow system. For instance, a crystal developing in a vug will tend to grow most rapidly on the side that faces the direction of flow. The reason for the different rate of growth is that material is directly and continuously fed to the flow (stoss) side, whereas the lee side is fed largely by diffusion and receives less material. Therefore, an estimate of the direction of flow of solutions through a vug may often be made by collecting oriented crystals, sectioning them and analyzing their growth zones for differences in development.

The flow direction can also be determined by analyzing crystal asymmetry, overgrowths on crystals, preferred corrosion of crystal faces, and preferred growth of lineage structure. There are a number of precautions that must be taken in the application of this method (10, 11) but under favorable conditions it has been shown, notably by Stoiber (23) in the Pitcher Creek field in the Tri State zinc-lead area, that the method is reasonably practical to apply in some mines.

Pressure of Formation of Hydrothermal Minerals.—In this technique an estimate is made of the relative pressure of formation of samples of some hydrothermal mineral (usually quartz) taken throughout the area to be examined (19, 20). When the pressures have been established the direction of flow is determined as being from areas of higher pressure to areas of lower

pressure. In other words, the solutions flow down the established pressure gradient the same as water does when it runs out of a tap.

An estimate of the relative pressure of formation of a sample is made by first obtaining the temperature at which liquid inclusions in the mineral decrepitate. The decrepitation temperature (the temperature at which the gas phase disappears in a liquid inclusion) is a function of two variables—the temperature and the pressure of the formation of the mineral. Consequently, the pressure of formation can be determined if values for temperature are known.

There are several ways of estimating the relative temperature of formation of minerals from place to place in a deposit.

a. If pyrite is present in the deposit, according to Smith (18), an idea of the temperature of deposition may be obtained by using the pyrite geothermometer.

b. If the samples are taken from a restricted area in a mine, such as a single stope, then the temperature of deposition probably does not vary to any great extent within the area and the temperature may be assumed to be constant.

c. If there is a distinct zoning of minerals in the mine, the metal-ratio contours may be assumed to be parallel to lines of equal temperature; the distribution of the isotherms obtained in this way may be used to make some adjustments to the decrepitation results.

d. If samples are taken over a large area, such as through several levels of a mine, and if there is no other information such as pyrite temperatures, it is usually reasonable to assume that the temperature decreases upwards. In this case only an approximation of the pressure drop through the mine can be obtained.

Objections to the decrepitation technique have been raised (12, 16). Spurious results may be obtained by leaking of the inclusions, development of secondary inclusions, and so forth, and there is no doubt that the method has to be used with care. On the other hand, the results may be obtained quickly, particularly in deposits with a quartz gangue, and if supported by evidence from other flow techniques, the method is believed to be reasonably reliable and should have a wider application to problems of flow.

Regional Method by Chemical Analyses.—The direction of flow may be determined on a regional scale. It is an empirical fact that ore is often found around the boundaries of granitic type rocks that may be either igneous or sedimentary in their origin. In these cases it is usually assumed that the ore is derived from solutions that flow out of the central part of the granitic mass towards its contacts. The direction of flow of solutions from these granitic bodies may be estimated by analyzing samples, taken from the surface, for products such as silica, radioactive elements, and so forth, that either crystallize late from a cooling magma, or go into solution early in sediments that are being heated. The direction of flow is indicated by the piling up or increase in quantity of these elements within the granitic mass.

A number of granitic bodies have been investigated (11) and an example of the application of this method is shown on Figure 1. Four major concen-

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trations of gold ore are known to occur around the eastern boundaries of the granitic body as shown by shaft symbols on the figure. Considerable surface and underground exploration has been done around the other contacts but no ore has been found. The figure shows the increase in silica in the vicinity of the known ore, which is interpreted as being due to flow of late products within the granitic mass moving towards structures that now house the ore. The technique has no application around a mine but may be useful in the prospecting of new districts or the reprospecting of old areas.

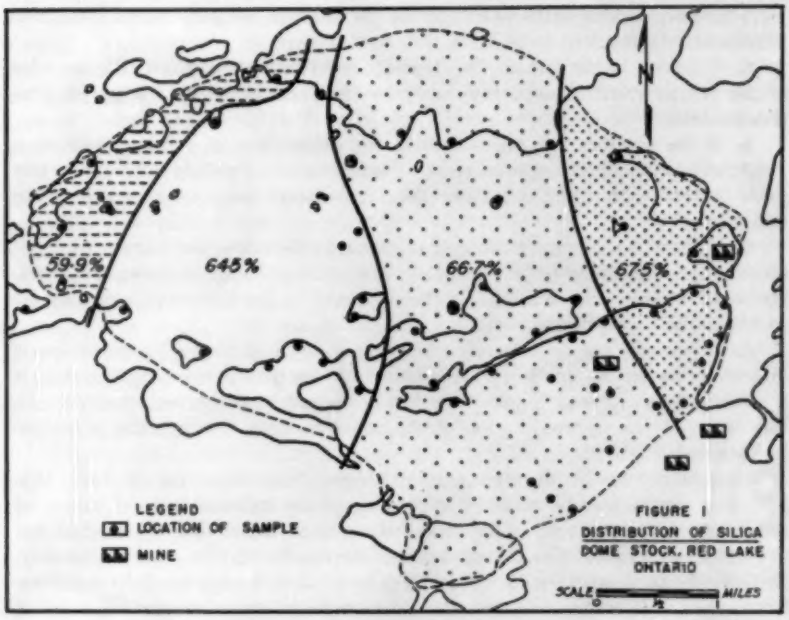

FIG. 1.

THE BLYKLIPPEN MINE

General

The ore body at the Blyklippen mine is used to illustrate the application of the flow techniques to a mine problem. A brief description of the geological setting of the mine is given so that the reader may follow, more easily, the picture of the flow direction of the ore-bearing solutions as it is developed below. Further details of the general geology of the region around the mine can be obtained in publications by Kock (13), Witzig (23), and Brown (4).

The mine is located on the east coast of Greenland at latitude 72° 15′ north. A sketch of the geology in the vicinity of the mine is shown in Figure 2. At first glance the map appears rather complicated, but a look at the cross section

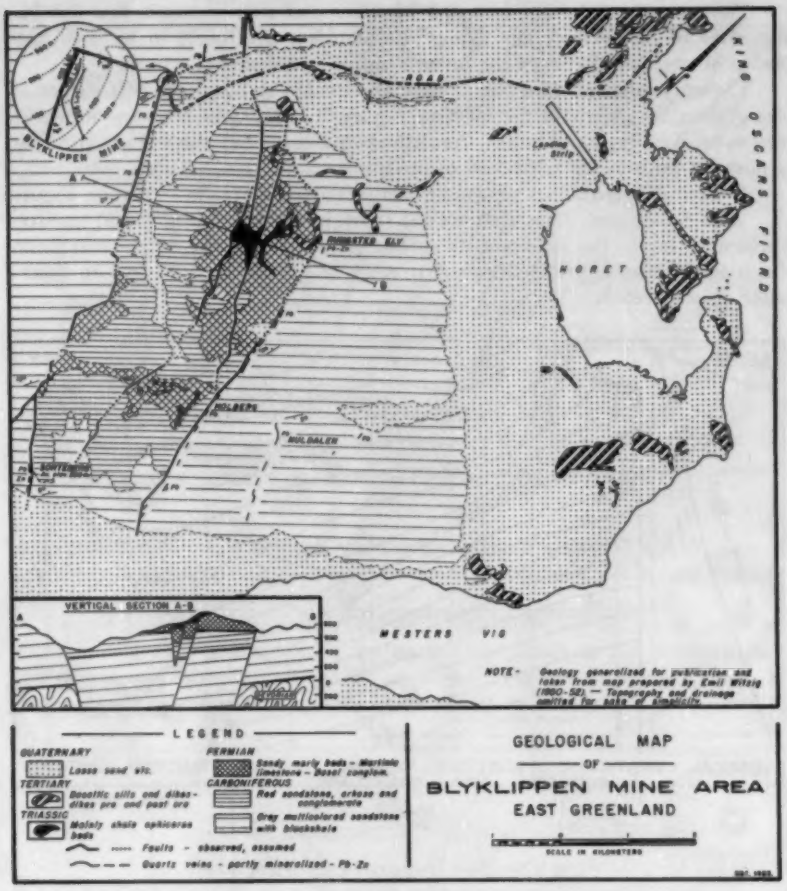

FIG. 2.

that is inset above the legend will show that relatively flat-lying sediments, principally sandstones, arkoses, and conglomerates, are down faulted into a fairly simple graben structure. The younger sediments occur in the trough and the disposition of the sediments appears complicated only because of the rugged nature of the topography.

The faults are all normal and are generally filled with irregular masses, lenticular veins and stockworks of banded to crystalline quartz. Barite forms the only other common gangue mineral. There are many places along the main fault zones that contain galena, sphalerite and in places a small amount of chalcopyrite. Other sulphides are rare.

The country rocks are intruded by dikes and sills of basalt that are believed to be of Tertiary age (24). Basalt dikes are found to be both pre- and post-ore, and therefore the mineralization is dated as Tertiary.

The only mine workings at present are located at the northwest corner of the graben, as shown in the inset in Figure 2. The lead-zinc ore occurs in the north-west trending fault. According to Brown (4) the ore is cut off by a post-ore fault at the north end of the mine.

A vertical longitudinal section of part of the mine area is shown on Figure 3. This figure and those that follow show in common the ground surface, three mine levels, the approximate outline of the ore and the north-cross fault. Each succeeding figure is designed to show a specific feature used to determine flow direction.

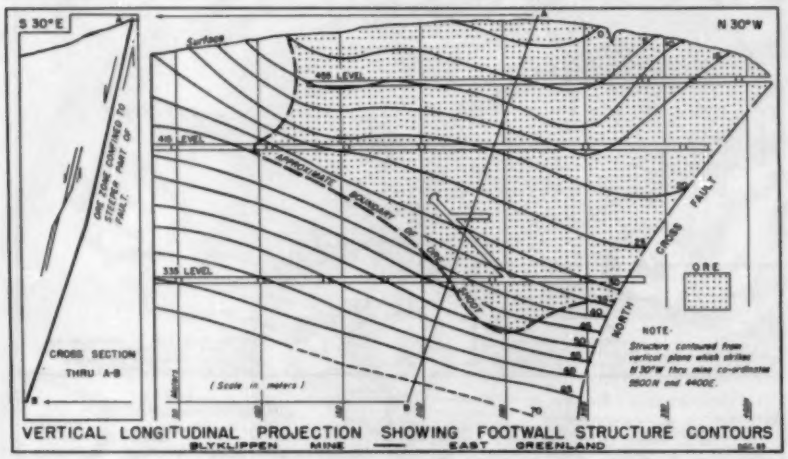

FIG. 3.

Flow Direction Suggested by Structure

Figure 3.—The footwall of the fault zone has been contoured from a vertical plane shown on Figure 3. It can be seen that the ore zone coincides quite closely with a steep section of the fault. As the hanging wall moved down during faulting, it is possible, or even likely, that the steep section of the fault, now housing the ore, opened in a manner shown on the left of Figure 3; a low pressure area would be created and available ore solutions would tend to flow into this area. Although this analysis does not indicate the flow direction, the conception of differences in pressure initiates thinking in terms of solution movement.

Figure 4.—Isopachs showing the width of the fault containing the ore zones are shown on Figure 4. It may be seen on Figure 4 that the fault decreases in width from 55 m to 5 m along the length of the ore shoot. It may

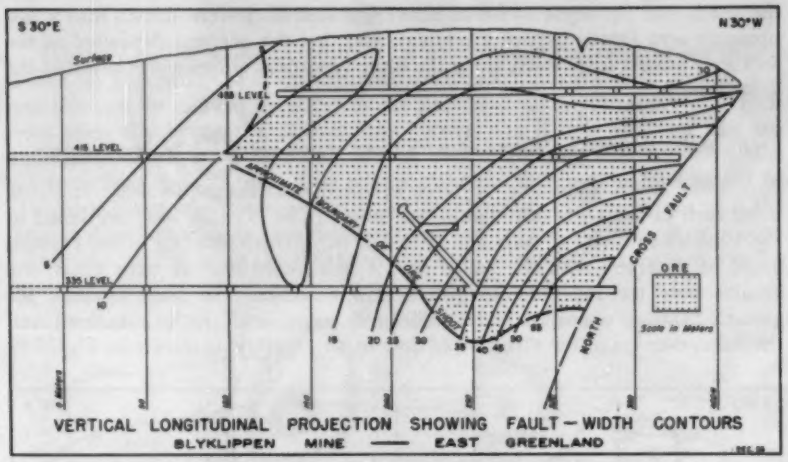

FIG. 4.

be expected that the wider the conduit the greater would be the volume of flow along it, in which case the greatest volume of solutions would flow through the fault at the northern end of the mine.

Figure 5.—This figure shows that the width of the ore decreases from the northern end (at the junction of the north-cross fault) to the southern part of the mine. Combining this observation with Figures 2 and 3, it may be reasonable to assume that the bulk of the solutions entered the mine area at

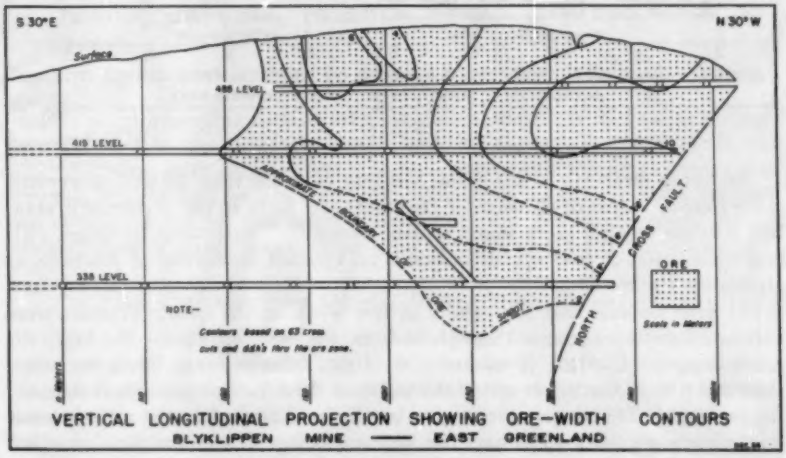

FIG. 5.

the north end (greatest width of fault) and that they were drawn into a low pressure area (steep part of the fault), and that the ore was deposited as the solutions moved southward along the fault (decrease in ore-width towards the south).

Flow Direction by Growth Banding and Asymmetry in Quartz Crystals

Figure 6.—A minimum of three oriented quartz crystals were collected from each of fourteen locations in the mine. The crystals were sectioned at right angles to their "c" axis and although the growth banding in the crystals could be observed with the naked eye, it was found that, in most cases, the results were too indefinite to give a flow direction. In some crystals the growth banding appeared to be sufficiently asymmetric to be measured and the interpretation of the direction of flow by this method is shown on Figure 6.

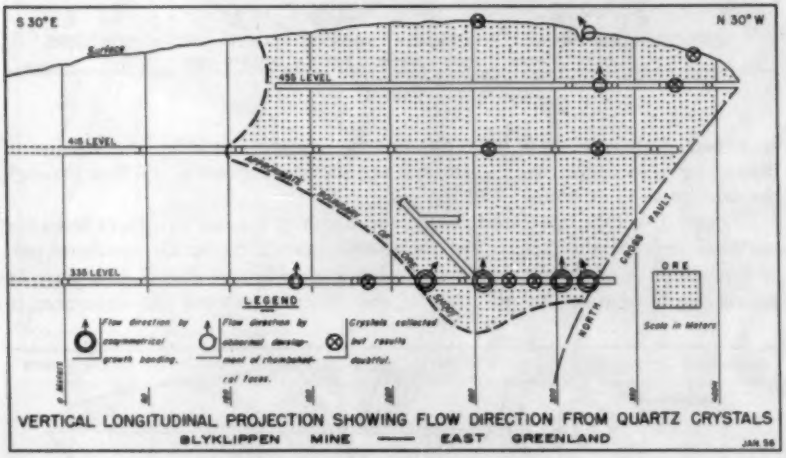

FIG. 6.

In three locations in the mine, clusters of more than 20 quartz crystals were found. Most of the smaller rhombohedral faces in the asymmetric crystals in these groups were found to face upwards. According to Engel (9), this orientation of the crystals indicates an upward movement of solutions as shown on Figure 6.

It must be said that the results of this work on the quartz crystals were rather indefinite, perhaps through lack of sufficient material. At best, the work suggests that the flow direction of the solutions was upwards rather than down from the top or out of the walls, at the time the quartz was depositing in vugs. This vug quartz is the last to be deposited in the mine so that flow direction at this stage may not necessarily agree with the flow direction at the time of the earlier lead-zinc-quartz mineralization.

Flow Direction from Mineral Zoning

Figure 7.—The lead-zinc ratios from several hundred samples are represented on Figure 7. It is evident that there is a marked zoning of lead and zinc through the mine as indicated by the lines of equal metal-ratio. Age relations show that sphalerite is later than galena, and if it is assumed that the mineralization changed from zinc to lead with a lowering temperature as the solutions flowed away from their source, then the direction of flow would be at right angles to the contour lines. As this direction of flow agrees with the general direction obtained by the structural and crystal analyses, it would be reasonable, at this stage, to represent the flow direction by an arrow on the figure.

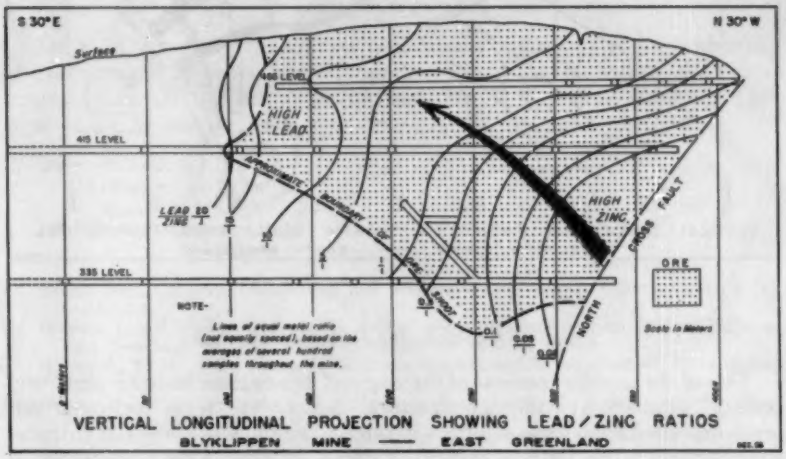

FIG. 7.

It is worth recording that, as far as is known, the silver-lead ratios through the mine vary in the same way as the lead-zinc ratios. In other words, the silver decreases with depth which is in accordance with the zonal sequence of minerals as proposed by Emmons (7). The silver in the ore runs less than one ounce per ton so that silver assays were not commonly made and, at present, there is insufficient data on hand to make into a reliable diagram.

Flow Direction from Quartz; Decrepitation Temperatures

Figure 8.—Decrepitation temperatures from 34 samples of quartz have been contoured as shown in Figure 8. Assuming that the mineralization changed from zinc to lead with lowering temperature in accordance with the zonal theory, then as pointed out above, metal-ratio contours would be parallel to the isotherms at the time of deposition. It may be seen on Figures 7 and 8 that the decrepitation temperature and the lead-zinc ratio contours (isotherms)

are roughly parallel. In this case, the pressures of formation are inversely proportional to the decrepitation temperatures. Therefore the direction of flow is at right angles to the decrepitation temperature contours (isobaric lines) as shown by the arrows on Figure 8.

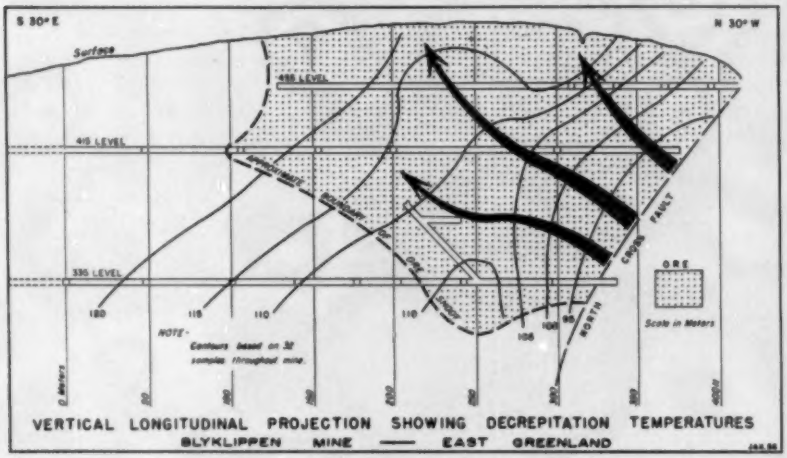

FIG. 8.

Value of Knowing the Direction of Flow

One of the popular concepts of the origin of primary ore bodies is that "ore-bearing" solutions flow through structural channelways in the rocks and that ore is deposited from these solutions in certain favorable physical and chemical environments within the flow system. In his work around the mine the geologist usually tries to compile as many facts as possible concerning the environment of the known ore bodies and exploration for new ore usually depends on testing other areas around the mine which are presumed to possess a similar environment. It is suggested that determining the direction of flow may enable the geologist to select for exploration a favorable environment within the flow system which, it is maintained, would have a better chance of containing ore than similar environments outside the flow system.

The flow picture that has developed at the Blyklippen mine can be used in a number of ways. For example, to help select areas to be tested for the occurrence of ore the characteristics of the flow pattern (as well as the general set-up) suggests that the north-cross fault is not post-ore but that in all likelihood the solutions entered the country at the junction of the two fault systems and that the known ore spilled into a low pressure area which now houses the main ore body. Therefore, it was considered that the north-cross fault could also contain lead and zinc mineralization. Recent work has substantiated this claim.

If the ore solutions entered by the fault junction then exploration at depth will be designed to locate steep sections (low pressure areas) in either of the two faults.

Of course, other factors in the general environment, such as the composition of the wallrock, wallrock alteration, and so forth, must also be taken into account. Furthermore, epithermal mineralization of the Blyklippen type generally indicates a limited vertical range of deposition so that exploration built on flow direction alone may be fruitless. On the other hand, it seems clear that knowledge of the flow direction is helpful in building up general ideas for the search for ore and it is hoped that the suggestions given in this paper will be of some use to those wishing to apply the method.

ACKNOWLEDGMENTS

Dr. G. B. Langford, head of the Department of Geology of the University of Toronto, and Professor R. E. Deane were kind enough to read the manuscript and to offer constructive criticism. Mr. D. G. Evans helped prepare some of the figures.

DEPT. OF GEOLOGY,
UNIVERSITY OF TORONTO,
March 8, 1956

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SOME OBSERVATIONS ON SYNGENETIC ORES

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ABSTRACT

Some of the relationships that might be used in determining whether the ores are syngenetic or epigenetic are discussed. Some experiments were run to determine the amount of comminution of silicate rocks and sulfide ores in a stream environment. The possible equations that might produce covellite, chalcopyrite and bornite are cited.

In any classification of ore deposits there are compartments for those orebodies that are syngenetic and supergene and there are quite distinct compartments for deposits that are epigenetic and either supergene or hypogene. To have these distinctions on paper is one thing, but to place a deposit in the field in its proper category is another.

A perusal of recent papers on the origin of the copper ores of Northern Rhodesia, or to go back even further to the various theories that have been advanced for the origin of the Clinton iron ores or for the gold on the Witwatersrand, shows the difficulty of placing these deposits in their proper categories.

There should be some criterion to help the geologist in the field and the purpose of this paper is to point out some. In order that there be no misunderstanding the problem is stated thus: Suppose there are two beds, which are not in the same place geographically. Both beds are composed of noncalcareous clastic sedimentary grains and both beds are mineralized. What are the characteristics that would determine whether the mineralization is syngenetic or epigenetic?

(i) The presence of feeder veins entering the bed would point to an epigenetic origin. However, the absence of such veins would not constitute positive evidence for a syngenetic origin.

(ii) The same evidence applies to dikes that may have intruded the beds, unless the beds adjacent to the intrusives show clearly by their tenor a high mineral content. An example of these difficulties will be appreciated from a study of the papers by Mellor, Graton, and Reinecke dealing with the Witwatersrand.

(iii) The presence nearby of a large body of intrusive plutonic rock has usually been considered as positive evidence for epigenetic ore.

(iv) When the minerals within the beds jump from one horizon or layer to another the usual interpretation has been that this is evidence of an epigenetic origin. However, even this relation has been challenged and metamorphism invoked to explain the jump.

(v) Even if the ore minerals definitely replace the rock minerals of the bed, the evidence is not conclusive, as a perusal of Twenhofel's discussion of the Precambrian hematites will show. It would appear that the chemical characteristics of the particular ore mineral have to be considered. Hematite will not behave in the same way as chalcopyrite.

(vi) The question of grain size may offer some solution to the problem. Two cases may be considered:

Case I. All grains rounded and reduced in diameter to sizes given by Twenhofel (12) favor a supergene syngenetic origin.

Case II. All grains angular.

Twenhofel (12) makes the following statement—"It is the author's considered opinion that rounding of sand grains below the dimensions of 1 mm involves extremely long transportation no matter whether the sands are transported by streams or along and on beaches." Ziegler (13) prefers a lower dimension of 0.75 mm, after which there is no effective rounding.

If ρ_{om} is the density of the ore mineral and ρ_{rm} the density of the rock mineral and V_{om} and V_{rm} the volumes of the grains, respectively, then for a given velocity of transport the mass of the grains of the ore minerals and rock minerals will be the same, it follows then that

$$V_{om} \times \rho_{om} = V_{rm} \times \rho_{rm}$$

and consequently if $\rho_{om} > \rho_{rm}$ then V_{om} will be $< V_{rm}$.

The following deductions may then be drawn: If the deposit is syngenetic, then $V_{om} < V_{rm}$; if $V_{om} > V_{rm}$ then the deposit cannot be syngenetic.

For an epigenetic deposit the grain size of the ore mineral can bear any relation to the grain of the host rock. However the grains of the ore minerals will not bear the same textural relation to the rock grain that these do to each other.

Garlick (1955) states that, "the Northern Rhodesian copper ores were transported mainly in solution; probably as sulphates or chlorides and deposition is attributed to biochemical processes in stagnant water."

Chemically this transfer may be represented as follows:

$$CuCl_2 + 2\,Fe(OH)_3 + H_2S \rightarrow CuS + Fe_2O_3 + 2\,HCl + 3\,H_2O$$

or

$$CuSO_4 + 2\,Fe(OH)_3 + H_2S \rightarrow CuS + Fe_2O_3 + H_2SO_4 + 3\,H_2O.$$

F. W. Clark (4) cites experiments by Durocher (1855), in which covellite (CuS) was formed by the addition of hydrogen sulfide to copper chloride, and Doelter (1886) who gently heated copper oxide with hematite and hydrogen sulfide and obtained chalcopyrite.

$$4\,CuO + 2\,Fe_2O_3 + 8\,H_2S \rightarrow 4\,Cu\,FeS_2 + 8\,H_2O + O_2.$$

He also made bornite from cuprite, tenorite, hematite and hydrogen sulfide at temperatures between 100°–200° centrigrade.

$$8\,CuO + Cu_2O + Fe_2O_3 + 8\,H_2S \rightarrow 2\,Cu_5FeS_4 + 8\,H_2O + 2\,O_2.$$

These experiments suggest that the common mineral found in the Rhodesian ores should be covellite. The problem is therefore to show how covellite can be changed to chalcocite, chalcopyrite and bornite by metamorphism.

To further the ideas already presented a series of experiments was conducted to confirm and extend the work previously done by Anderson (1) on the rounding and wear of particles that accumulate as sediments.

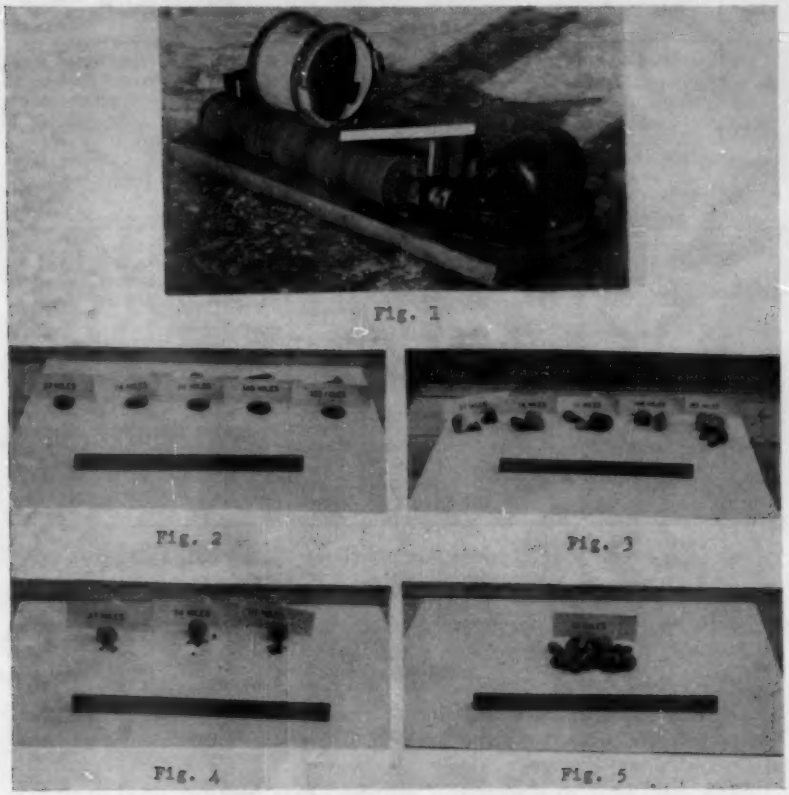

FIG. 1. The Mill.

FIG. 2. Quartz-rich sand. Average diameter 0.37 mm. Experiment shows no reduction in size of material over the range of miles.

FIG. 3. White pebbles granite, grey pebbles Halifax slate. At start angular. Experiment shows that there is little change in rounding from 37 to 185 miles.

FIGS. 4 AND 5. Pyrite. Average diameter greater than 1 mm. Experiment shows that the pyrite pebbles are well rounded after 10 miles and further travel only tends to produce more fine material.

For these tests a ball mill whose rotation would approximate stream flow was used. Running at a speed of 1.54 M.P.H. any cascading effect was eliminated by varying the amount of water in the mill to the size and type of particle used.

The following table gives the results of these runs.

EXPERIMENTS ON WEAR AND ROUNDING OF ROCK PARTICLES

Test	Rock type	Size	Sample	Distance travelled (in miles)	Remarks
1	Quartz-rich sand	Average diameter 0.37 mm	1	37	No observed rounding of fragments. The average diameter of the fragments does not change.
			2	74	
			3	111	
			4	148	
			5	185	
2	Granite, quartzite and slate. All angular fragments	Average diameter greater than 1 mm	1	37	Fragments rounded at 37 miles. Fine material produced of minute size which cannot be measured on a microscope of 625 magnification.
			2	74	
			3	111	
			4	148	
			5	185	
3	Pyrite. All angular fragments	Average diameter greater than 1 mm	1	37	Fragments rounded at 37 miles. Fine material too small to measure.
			2	74	
			3	111	
4	Pyrite. All angular fragments	Average diameter greater than 1 mm	1	10	Large fragments rounded and similar to stream pebbles. Fine material as in other runs.

CONCLUSIONS

There is no appreciable rounding of grains with a diameter of less than 1 mm due to the protective film of water. This result confirms the statements by Twenhofel and Ziegler.

These tests seem to suggest that if sulfides have been subjected to stream transport the amount of 0.0039 (1/256) mm material will be considerable and should therefore be found in the tailings of any concentration process involving grain size. It is common practice in ore dressing to crush to a minimum size of mineral grain observable under the microscope. Therefore, it is concluded that if a deposit is of supergene syngenetic origin with little or no subsequent metamorphism, a considerable proportion of the sulfides should be found in the finest grade of rock particles.

It is possible that this very fine comminuted material might go into solution and be deposited in a sediment at a final resting place. The consequence of this behavior would be classified as a supergene epigenetic deposit. One of the ear marks of such a deposit would be that the sulfide grains would exhibit crystal outline either idiomorphically or allotriomorphically and not sub-angularity.

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March 19, 1956

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STABILITY OF MINERALS IN THE SYSTEM ZnO-SiO_2-H_2O [1]

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ABSTRACT

An experimental study of the phase equilibria in the system ZnO-SiO_2-H_2O has been made at elevated temperatures in the range 130° C to 780° C employing water vapor pressures from 500 to 40,000 pounds per square inch. Stability regions were established for several minerals in this system, which occur naturally in the oxidized zones of lead and zinc deposits. Hemimorphite was found to be stable up to about 250° C at 20,000 psi., while above this temperature, willemite plus water are in equilibrium. With suitable qualifications this temperature may be taken as the maximum temperature of formation and stability of hemimorphite as well as the minimum for willemite. The pure zinc oxide-silica end member of the montmorillonoid-type mineral, sauconite, was found to be stable up to 210° C, although natural sauconite, containing alumina is stable to approximately 125° C higher. Uncertainties still remain in the determination of the $Zn(OH)_2 \rightleftharpoons ZnO + H_2O$ equilibrium, and for that reason studies of the reaction $ZnCO_3 \rightleftharpoons ZnO + CO_2$ may prove to be more significant in determining the minimum temperature of zincite formation.

[1] Contribution No. 55-49, College of Mineral Industries, The Pennsylvania State University. Presented at the 1955 Annual Meeting of the Mineralogical Society of America, New Orleans, La., November 7–9.

INTRODUCTION

THE system ZnO-SiO_2-H_2O contains, in addition to the several forms of silica, three minerals common in oxidized zinc deposits: hemimorphite (calamine), willemite, and sauconite, as well as the rare mineral zincite. Although sphalerite is perhaps the most important ore of zinc, the former minerals are important in sulfur-deficient metamorphosed deposits, or in the zone of oxidation. A determination of the equilibria among phases in the system zinc oxide-silica-water should therefore be significant for the interpretation of the conditions of formation in areas where the mineral composition approaches that defined by the system.

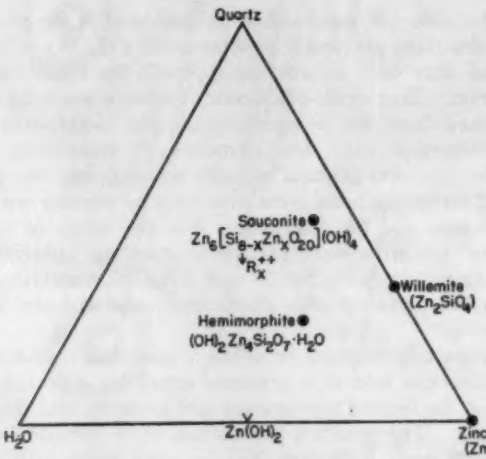

FIG. 1. Composition of phases in the ZnO-SiO_2-H_2O system.

The compositions of the minerals are shown in the triangle of Figure 1. Studies of the stability of montmorillonite-type minerals (12), included syntheses of an aluminum-containing sauconite comparable to the natural mineral, as well as a pure zinc oxide-silica ($-H_2O$) end member. The theoretical composition of this phase is plotted in Figure 1, based on the assumption that Zn^{++} substitutes for silicon in the tetrahedral position. The system ZnO-SiO_2 was studied by Bunting (1) and contains one congruently melting compound, Zn_2SiO_4, the high temperature form of which is willemite. Two other forms of Zn_2SiO_4 have been reported formed on cooling from high temperatures (20), but under hydrothermal conditions of synthesis only willemite was reported (7). The empirical formula of hemimorphite differs from that of willemite by the addition of one water molecule, but structural work, as well as weight loss determinations suggest that the H_2O is present in two forms, hence, the formula $(OH)_2Zn_4Si_2O_7 \cdot H_2O$ (8). In systematic studies of possible serpentine-type structures (16) neither a zinc phase analogous to

$Mg_3Si_2O_5(OH)_4$, nor a talc analogue was noted. Although not reported to occur naturally, zinc hydroxide has been described, with varying degrees of certainty, as existing in six polymorphic forms (five crystalline and one amorphous) (5). Most of the previous work on the system ZnO-H_2O has been at room temperature and atmospheric pressure.

The present investigation was undertaken for the systematic determination of equilibria among the phases in the ZnO-SiO_2-H_2O system. These data will be useful in the interpretation of conditions of formation of natural zinc minerals, and will also provide further information on the synthetic counterparts.

EXPERIMENTAL PROCEDURE

The hydrothermal equipment and techniques used in the present investigation have been described previously in some detail (17, 18). Several types of starting material were used in order to approach the equilibrium from more than one direction. Zinc oxide-silica mixtures were made by decomposition of the gel formed from the evaporation of zinc nitrate-ethyl orthosilicate mixtures. Considerable care was exercised to completely eliminate the nitrate from the mixtures without actually crystallizing the gel. Chemical precipitates and oxide mixtures were also used as starting materials as well as natural willemite and hemimorphite. For the study of zinc hydroxide equilibria several mixtures were prepared, including materials precipitated from solution of zinc salts with NaOH and NH_4OH, materials formed by the decomposition of zinc oxalate with alkali; zinc metal and zinc amalgam were also used.

A particular starting material, or series of materials contained in platinum or gold envelopes, was held in a pressure vessel for a period varying from hours to weeks at the desired temperature and pressure, and then quenched to room temperature. The products of reaction were identified by X-ray diffraction techniques using a Phillips Norelco wide range diffractometer, and by petrographic examination where possible. In some instances weight loss determinations were made and infra-red spectra were obtained on a Perkin-Elmer Model 21 double-beam spectrometer.

EXPERIMENTAL RESULTS

Pressure-Temperature Diagram

The data obtained from the present experimental study of the system ZnO-SiO_2-H_2O are summarized in Table I. These results are best illustrated by a temperature-pressure diagram such as that in Figure 2. The three univariant curves in Figure 2 describe the equilibria from left to right for the following reactions:

$$\underset{\text{sauconite}}{Zn_{3-x}(Si_{4-y}Zn_y)O_{10}(OH)_2\cdot Zn_{x+2y}} = \underset{\text{hemimorphite}}{Zn_2SiO_4\cdot H_2O} + \underset{\text{silica}}{SiO_2} + \underset{\text{water}}{H_2O} \qquad (1)$$

$$\underset{\text{hemimorphite}}{Zn_2SiO_4\cdot H_2O} = \underset{\text{willemite}}{Zn_2SiO_4} + \underset{\text{water}}{H_2O} \qquad (2)$$

$$\underset{\text{zincite}}{Zn(OH)_2} = ZnO + H_2O \qquad (3)$$

These curves delineate stability regions for those phases shown in the p-T diagram. For example, to the left of the first curve sauconite was found to be stable, breaking down at the curve to yield hemimorphite plus silica [2] plus water. At 20,000 psi (pounds per square inch) this reaction would take place at 210° C. Similarly to the left of the second curve hemimorphite is

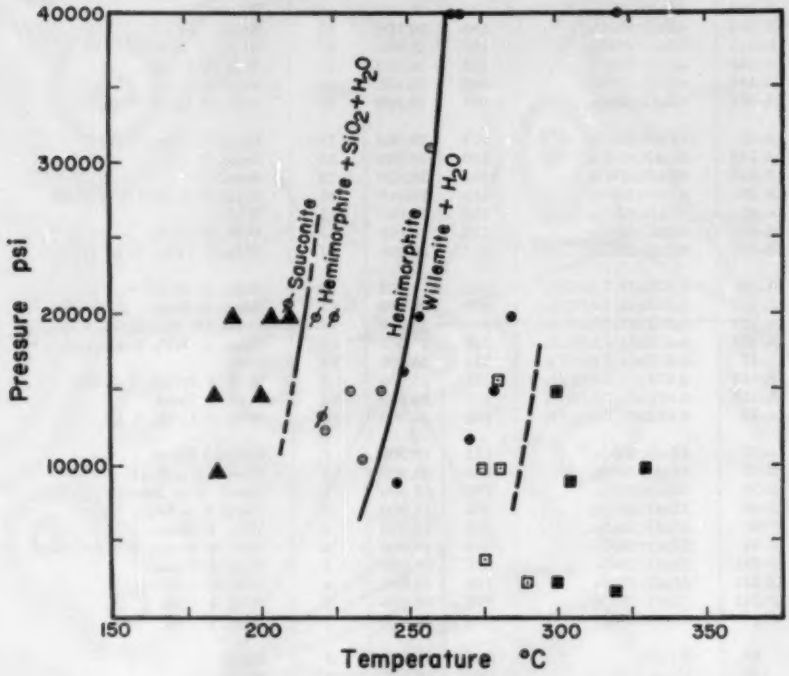

FIG. 2. The system ZnO-SiO_2-H_2O. Univariant p-T curves are determined by data of Table II. Phases are represented as follows: *For Curve I:* ▲ = sauconite, ϕ = silica + hemimorphite (or metastable willemite). *For Curve II:* ○ = hemimorphite, ● = willemite. *For Curve III:* □ = $Zn(OH)_2$, ■ = ZnO.

stable, breaking down to the right of the curve into willemite plus water. The temperature for this reaction varies from about 240° C at 10,000 psi to 260° C at 40,000 psi. The third curve, in dashed lines is very questionable, but may represent the equilibrium for $Zn(OH)_2 \rightleftarrows$ zincite + H_2O. This will be discussed in more detail later.

[2] Although the stable phase under these p-T conditions is quartz, in many cases cristobalite is crystallized metastably, and hence "silica" is used to describe the product, in order to avoid ambiguity.

TABLE I

SUMMARY OF THE EXPERIMENTAL RESULTS IN THE SYSTEM ZnO-SiO_2-H_2O

Sample composition		Temp. (° C)	Pressure (psi)	Time (days)	Products*
Number	Molar ratio				
A-368	$4ZnO:8SiO_2$	191	20,000	18	Sauc.
A-304	$4ZnO:8SiO_2$	198	20,000	14	Sauc. (?)
A-341	$4ZnO:8SiO_2$	207	20,000	27	Sauc. + Will. + Crist.
A-446	$4ZnO:8SiO_2$	218	20,000	14	Will. + Crist.
A-445	$4ZnO:8SiO_2$	240	20,000	14	Will. + Crist.
A-378	$4ZnO:8SiO_2$	507	20,000	14	Will. + Crist. + Q. (?)
A-18	$6ZnO:8SiO_2$	173	20,000	13	Sauc. + Hemi.
A-128	$6ZnO:8SiO_2$	190	20,000	15	Sauc. + (?)
A-218	$6ZnO:8SiO_2$	203	20,000	13	Sauc.
A-392	$6ZnO:8SiO_2$	210	20,000	15	Sauc. + s. Will + s. Crist.
A-46	$6ZnO:8SiO_2$	213	20,000	12	Will.
A-318	$6ZnO:8SiO_2$	225	20,000	12	Will. + Crist.
A-377	$6ZnO:8SiO_2$	507	20,000	14	Will. + Crist. + Q. (?)
A-19	$6.67ZnO:7.67SiO_2$	173	20,000	13	Sauc. + Hemi.
A-129	$6.67ZnO:7.67SiO_2$	190	20,000	15	Sauc. + Hemi., + Q. (?)
A-219	$6.67ZnO:7.67SiO_2$	203	20,000	13	Sauc. (?) (v.l.c.)
A-393	$6.67ZnO:7.67SiO_2$	210	20,000	15	Sauc. + Will. + s. Crist.
A-47	$6.67ZnO:7.67SiO_2$	213	20,000	13	Will.
Z-149	$6.67ZnO:7.67SiO_2$	221	13,000	3	Will. + Hemi. + Crist.
A-319	$6.67ZnO:7.67SiO_2$	225	20,000	13	Will. + Crist.
A-73	$6.67ZnO:7.67SiO_2$	401	20,000	10	Will. + Crist. + Q.
5477	$3ZnO:2SiO_2$	175	10,000	7	Largely Hemi.
Z-75	$3ZnO:2SiO_2$	183	15,000	2	Hemi. + s. Sauc.
Z-70	$3ZnO:2SiO_2$	190	8,000	1	Hemi. + tr. Sauce.
Z-90	$3ZnO:2SiO_2$	200	15,000	8	Hemi + s. Sauc. (?)
5100	$3ZnO:2SiO_2$	225	15,000	4	Will. + Hemi.
Z-94	$3ZnO:2SiO_2$	234	10,000	5	Will. + Hemi. + s. Crist. (?)
Z-251	$3ZnO:2SiO_2$	257	31,000	1	Will. + Hemi.
Z-247	$3ZnO:2SiO_2$	268	40,000	4	Will. + s. Crist.
Z-242	$3ZnO:2SiO_2$	320	48,000	1	Will. + Crist.
5129	$3ZnO:2SiO_2$	750	10,000	1	Will. + Crist.
88	Hemi.	200	15,000	8	Hemi.
150	Hemi.	230	15,000	1	Hemi.
92	Hemi.	234	10,500	6	Hemi.
181	Hemi.	245	9,000	10	Will. + Hemi.
154	Hemi.	240	15,000	1	Hemi.
193	Hemi.	248	16,500	10	Will.
135	Hemi.	253	20,000	3	Will.
249	Hemi.	257	31,000	1	Hemi.
253	Hemi.	264	40,000	7	Will.
245	Hemi.	268	40,000	4	Will.

* Abbreviations used:

Will. = Willemite
Hemi. = Hemimorphite (Calamine)
Sauc. = Sauconite
Q. = Quartz
Crist. = Cristobalite
v.l.c. = Very little crystallinity
s. = some
(?) = questionable
tr. = trace

Compatibility Triangles

The equilibria in the system ZnO-SiO_2-H_2O may be further illustrated by reference to the triangles[3] of Figure 3. The triangles show the assemblages of phases stable at equilibrium conditions from a given composition, within a range of pressures and temperatures described by the p-T curves of Figure 2.

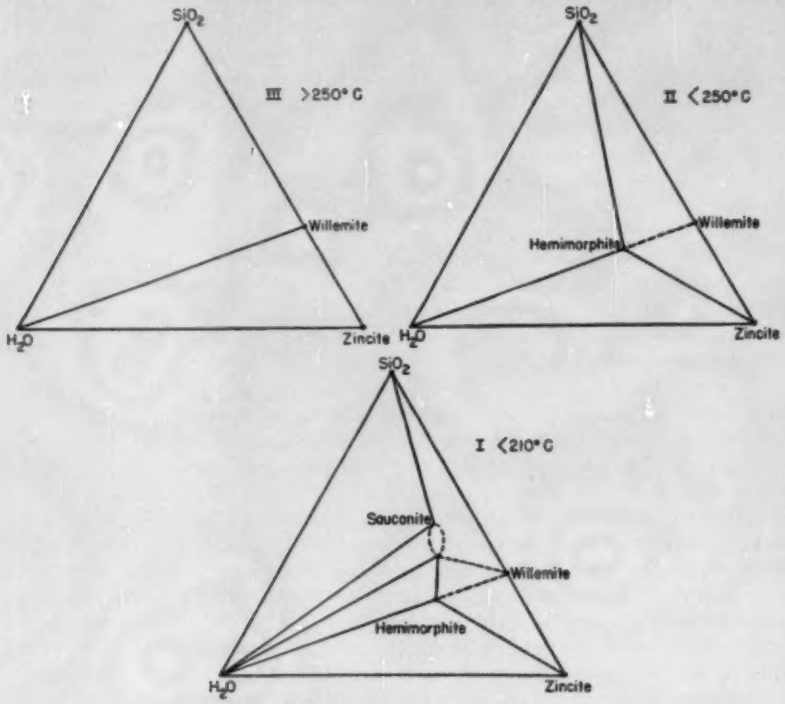

FIG. 3. Composition triangles for system ZnO-SiO_2-H_2O at 20,000 psi. Inner triangles represent experimentally determined combinations of three compatible phases. Dashed lines indicate probable assemblages in the presence of a deficiency of H_2O.

Temperatures indicated on the triangles apply for a pressure of 20,000 psi. Triangle I describes the phases compatible to the left of curve 1; triangle II between curves 1 and 2; and triangle III describes the compatible phases to the right of curve 2. Under the conditions of the experiments H_2O (always present in excess) is in each case one of the three compatible phases.

[3] For simplicity, and because of the tendency of ZnO to form (perhaps metastably) under a wide variety of conditions, $Zn(OH)_2$ is omitted from these triangles. Nevertheless, it is possible that the hydroxide is the equilibrium phase up to about 300° C or higher, in which case another triangle would be added to describe the equilibria up to these temperatures.

Sauconite Decomposition.—The first triangle represents the equilibria to the left of curve 1, i.e., where sauconite is stable. It is unfortunate that for the determination of the maximum temperature of stability of sauconite, the exceedingly slow reactions of mixtures at these low temperatures prevented extensive experimentation at pressures lower than 20,000; a few isolated runs at lower pressures, however, indicated roughly the same temperature for the reaction. Often either hemimorphite or cristobalite accompanies the sauconite, and there is some indication that the composition of the sauconite formed is variable, hence, this phase is plotted not as a single point, but as a small area. Compatible phases of this first triangle would then be those phases at the apices of the inner triangles: sauconite-silica-water, sauconite-hemimorphite-water, and hemimorphite-zincite-water. It may be postulated that if insufficient water is available to form hemimorphite, willemite will be stable and form at these lower temperatures. Although the maximum stability temperature of synthetic $ZnO\text{-}SiO_2(\text{-}H_2O)$ sauconite is only about 210° C, this does not mean that natural sauconite is not stable to higher temperatures. The natural mineral contains appreciable Al_2O_3, and Mumpton and Roy (12) have shown that synthetic Al-containing sauconites are stable as high as 335° C at 20,000 psi. Other examples of this "stabilization" of the montmorillonoid structure by alumina have been given by Roy and Roy (17) and Mumpton and Roy (12).

Hemimorphite Decomposition.—The second triangle represents the equilibria between curves 1 and 2 of Figure 2, where sauconite is no longer stable, and the compatible phases are hemimorphite-zincite-water and hemimorphite-silica-water. The curve describing the maximum stability of hemimorphite was determined in two manners: 1) Amorphous gel mixtures gave hemimorphite on the low temperature side of the curve and willemite above the curve; and 2) Natural hemimorphite decomposed to give willemite at temperatures higher than the curve, but remained optically clear and gave the characteristic hemimorphite X-ray pattern below the curve. When willemite was used as a starting material and subjected to hydrothermal treatment at temperatures below those of the second curve, no evidence of its rehydration to hemimorphite was obtained in the time of the experiments. Furthermore, no positive evidence has been obtained for the existence of a two-step equilibrium dehydration of hemimorphite; i.e., water molecules going off at one temperature and hydroxyl decomposition at another. Possible metastable step-wise dehydration was also studied.

DTA patterns of natural hemimorphite at atmospheric pressure showed a fairly sharp endothermic reaction at about 730° C, which is surprisingly high in view of the low equilibrium decomposition temperature (250° C at 20,000 psi). However, no evidence of a sharp endothermic reaction at a lower temperature was obtained. X-ray patterns of hemimorphite heated to temperatures above 600° C showed no change; static heating at 710° C showed partial breakdown.

Willemite Stability.—In the third and final triangle, hemimorphite is no longer stable and the remaining equilibrium assemblages are silica-water-

willemite, and water-willemite-zincite. Regardless of the mode of crystallization, whether from the decomposition of hemimorphite or by direct crystallization from gels, the alpha form of Zn_2SiO_4 has been the only form encountered in this study. Willemite is stable to the highest temperature of these experiments, about 750° C, and presumably much higher.

Properties of the Phases

Sauconite.—It was very difficult to obtain the end member sauconite from ZnO-SiO_2 mixtures as a single phase, and X-ray diffraction patterns fail to show a sharp reflection at 14.7Å characteristic of the (001) spacing of well-crystallized montmorillonoid minerals, but instead give a very broad intense background in this region. This broad "peak" accompanied by broad general reflections at about 4.4 and 2.6Å is indicative of poorly crystallized montmorillonoid-type minerals.

Under the electron microscope particles of the synthetic sauconite are extremely fine-grained, in the order of 0.1 μ. No distinctive morphology could be observed (which in itself is somewhat characteristic of this type of clay mineral).

Hemimorphite.—The hemimorphite used for determination of the curve hemimorphite $\rightleftarrows$ willemite + H_2O, was a well-crystallized pure sample from the Henrietta Mine, Leadville, Colorado, obtained from the Genth Mineral Collection, The Pennsylvania State University. The X-ray diffraction pattern and optical properties are in good agreement with the data of Swanson and Fuyat (21). Synthetic hemimorphite, although not as well-crystallized gave an X-ray pattern in good agreement with the natural mineral, with identical optical properties, as far as could be determined. As mentioned in the description of the equilibrium relations, no positive indication of a two-step equilibrium dehydration process of hemimorphite was obtained, the X-ray and optical of properties remaining the same up to the decomposition curve. Infra-red absorption spectra of the Leadville sample were obtained with the view of identifying two different types of OH^- vibration in the hydroxyl region of the infra-red spectrum. Although considerable care was taken to obtain a particle size sufficiently fine to give a well-resolved spectrum in the short wave-length region, only a single moderately broad absorption maximum at 2.9 microns was obtained. The rest of the spectrum was similar to that reported by Keller, Spotts and Biggs (9).

Willemite.—The optical properties of willemite formed in the present study are consistent with those of pure natural varieties, and the X-ray diffraction pattern compares well with that of the natural pale green variety from Mine Hill, N. J. Infra-red spectra obtained on both natural and synthetic varieties agree with that of Keller, Spotts and Biggs (9). No evidence was obtained for the stable existence of other Zn_2SiO_4 polymorphs in the temperature-pressure range studied.

Zincite.—The zinc oxide formed generally as tiny crystals having an X-ray diffraction pattern similar to that reported by Swanson and Fuyat (21). The intensities of the reflections differed somewhat from those re-

ported, the (100) being depressed and the (002) enhanced in the ZnO produced from the decomposition of $Zn(OH)_2$.

Zinc Hydroxide.—It has been extremely difficult to correlate the data obtained on $Zn(OH)_2$ with those in the literature, which in general are rather incomplete. Most of the materials obtained by low-temperature precipitation rapidly broke down to yield ZnO; some yielded a possible metastable hydroxide soluble under hydrothermal treatment (probably the β-form). Besides ZnO only one phase could be prepared reproducibly over a wide temperature range. On reacting zinc sulphate solution with ammonia and treating the resulting ammoniated precipitate under hydrothermal conditions, a new phase (presumably $Zn(OH)_2$) was formed over a fairly wide temperature range (125°–300° C). This phase, however, could not be identified with any of the several $Zn(OH)_2$ polymorphs reported in the literature, and is definitely not that of the so-called stable ϵ-form of Corey and Wyckoff (2). This new phase crystallized as poorly-formed aggregates to well-formed uniaxial (or very small 2V) negative plates having an index or refraction of about 1.686, and a characteristic X-ray diffraction pattern given in Table II.

TABLE II

X-RAY DIFFRACTION PATTERN OF $Zn(OH)_2$ PHASE

d(Å)	Rel. int.	d(Å)	Rel. int.
7.44	0.5	2.97	3
6.97	100	2.85	1
6.77	1	2.76	2
4.75	1	2.69	2
4.40	1	2.571	0.5
4.23	2	2.392	0.5
3.77	1	2.327	0.5
3.71	1	1.987	0.5
3.49	15	1.744	2
3.24	1	1.678	0.5
3.09	3		

The infra-red absorption spectrum was rather complex with four maxima in the OH^- vibrational region (in the range 2.76–3.02 microns). Weight loss was near the theoretical amount (18%), with a negative test for NH_3. This compound was unstable above 300° C at moderate water pressures (1,000–20,000 psi), yielding only ZnO. The significance of this decomposition temperature is questionable, however, since it could not be verified from other starting materials. Zinc amalgam and zinc metal shavings when treated hydrothermally yielded ZnO at much lower temperatures. Considerable work would still be required to positively assign stability regions to the various forms of $Zn(OH)_2$.

DISCUSSION

General

The stability relations of the phases in the ZnO-SiO_2-H_2O system provide some fundamental information on the crystallo-chemical behavior of Zn^{++}. In

a previous paper (16) it was noted that Zn^{++} must be either too polarizable or too large ($Zn^{++} = 0.83$ vs $Mg^{++} = 0.78$Å) to form layer lattice structures similar to those of Mg^{++}, particularly with respect to the serpentine structure. The stability of phases formed in the present study illustrate the very strong tendency of Zn^{++} to assume a coordination number of four with respect to oxygen. No layer-lattice analogue of either serpentine or talc, in which the cation would be present in 6-coordination was formed with Zn^{++}. An end member sauconite was formed, with considerable difficulty only in the presence of unreacted cristobalite and willemite or hemimorphite; and this phase decomposed at a relatively low temperature (about 210° C) to yield hemimorphite and then willemite (plus silica). In hemimorphite, willemite and zincite Zn^{++} is present in four-fold coordination. Although it is difficult to draw generalizations from the data on the $Zn(OH)_2 \rightleftarrows ZnO + H_2O$ equilibrium, the generalization that the hydroxides containing 6-coordinated Zn^{++} are relatively unstable with respect to the zincite structure containing 4-coordinated zinc, seems justified. At least one form of $Zn(OH)_2$ having the C-6 type structure (that of brucite) is very unstable (Feitknecht, 1938); and at best, the most stable $Zn(OH)_2$ structures yield zincite far below the decomposition temperature of brucite to periclase (about 660° C at 20,000 psi, see Roy, Roy and Osborn, 18). The ease with which ZnO is formed on precipitation from solutions of zinc salts even at room temperature, and its failure to be re-hydrated, is in line with this same tendency, and it is not surprising that $Zn(OH)_2$ has not been reported in nature.

Geologic Significance

Although sphalerite is by far the most important source of zinc, the zinc silicates and oxide are found in the oxidation zones of many sulfide ore bodies. Willemite, hemimorphite, sauconite (generally described as a "zinciferous tallow clay") and occasionally zincite are found where silification is prevalent, while smithsonite (the zinc carbonate), occurs where CO_2 seemed to be dominant. As previously mentioned, no occurrences of the hydroxide have been reported. The stability data obtained in this study may well be applied to the interpretation of known zinc deposits, where these minerals are found.

For relatively pure willemite, formed in the presence of excess water, a temperature of about 250° C may serve as a minimum temperature of formation. Of course, this temperature may vary for highly manganiferous varieties such as troostite, as well as for those formed from anhydrous systems. The origin of willemite is a rather controversial subject. Some would suggest fairly high temperatures of formation, either from hydrothermal solutions directly, or as replacement products, whereas others have suggested a low temperature. Studies of the deposits at Franklin and Sterling Hill, New Jersey, tend to favor a higher temperature of formation (14). On the other hand it has been proposed that most willemite is but a low temperature alteration products of primary sphalerite, or secondary hemimorphite (13). From the

present studies one would expect hemimorphite to be the stable phase formed at temperatures below 250° C, if sufficient water were present.

Hemimorphite and smithsonite are commonly associated as alteration products of primary zinc minerals in almost every kind of supergene environment. The abundance of hemimorphite in "low temperature zones" of zinc deposits, and its colloform structure both are in line with the conclusions drawn from the present study, that hemimorphite is formed at temperatures below 250° C probably by precipitation from circulating aqueous solutions. The effect of solid solution on the stability of hemimorphite is not known at present, but one might expect a reaction similar to the hemimorphite $\rightleftarrows$ willemite + H_2O to prevail if perhaps Mn were present, with troosite probably altering to the Mn, Zn hydrosilicate, hodgkinsonite.

The tallow clays originally were thought to be a mixture of hemimorphite and kaolinite, but more and more are being identified as the zinc montmorillonoid, sauconite, with perhaps some hemimorphite admixed. The field relations between zinc ore bodies and the associated zinc clays are not well established. In some cases the sauconite occurs in thick beds where apparently Zn^{++} from percolating solutions has replaced ions in pre-existing montmorillonite beds (10). This replacement theory is not unreasonable in view of the fact that it is relatively difficult to form a pure zinc-silica sauconite: given sufficient time Zn^{++} could presumably replace cations in the tetrahedral and octahedral positions of the montmorillonoid type lattice. Most natural sauconites are relatively impure; possible exceptions are those found at the type locality, in Saucon Valley, near Friedensville, Pennsylvania. The occurrences in general suggest a low temperature of formation, in agreement with the stability determined experimentally.

The absence of zinc hydroxide in natural deposits is not surprising in view of the readiness with which zinc oxide is formed even by precipitation at room temperature. The relative rarity of zincite in oxidized deposits may be the result of reaction with an abundance of $CO_3^{=}$ to form hydrozincite or smithsonite: for in the latter case the recent data of Harker and Hutta (6) give a minimum temperature of 300° C to 440° C at pressures of 10,000 to 40,000 psi for the decomposition of $ZnCO_3$ to yield zincite + CO_2. Furthermore, when silica is available the ZnO will react readily to form either hemimorphite, sauconite or willemite, depending on the composition, temperature and pressure.

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GEOLOGY AND GENESIS OF ULTRABASIC NICKEL–COPPER–PYRRHOTITE DEPOSITS AT THE PACIFIC NICKEL PROPERTY, SOUTHWESTERN BRITISH COLUMBIA [1]

AARO E. AHO

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ABSTRACT

This paper deals with geology and genesis of some pipelike nickel-copper-pyrrhotite deposits on the property of Pacific Nickel Mines in southwestern British Columbia. These deposits occur almost exclusively within a stocklike ultrabasic mass one and a half miles across. The ultrabasic body consists essentially of pyroxenite with cores of peridotite, with hornblendic replacement phases, and with a remarkable reaction margin of pegmatitic hornblendite. The mineralization consists of disseminated and massive pyrrhotite with subordinate pentlandite and chalcopyrite among fresh olivine, bronzite, augite, and hornblende. The ultrabasics intermingle with, and partly cut, a larger batholithic mass of genetically related diorites of Late Mesozoic age. Both rocks and ore are cut by small ultrabasic and gabbroic dikes, and by veins and alteration zones.

[1] Condensed and modified from a Ph.D. thesis submitted to the University of California at Berkeley in 1954.

Some of the ore occurs as sulfidic olivine-rich cores or shells with bronzitic borders, forming remarkably zoned, steeply plunging pipe- or parsnip-shaped magnesian ultrabasic structures 100 feet or more in diameter. These features suggest replacement origin. The remainder of the ore forms massive sulfide-silicate bodies similar in size, attitude, and mineralogy to the zoned ones but more irregular in cross section and showing flow lines, banding, drag folds, sharp contacts, inclusions, and hornblendic reaction rims—all suggestive of injection origin.

Genetic characteristics of other similar nickel deposits and rocks of the world are summarized and compared, then two theories are presented for genesis of the ore at Pacific Nickel. Magmatic segregation is suggested with injection of sulfides in an incipiently molten state (perhaps 700–800° C) followed by minor replacement and reconstitution. Alternatively, a new twist is added to the hydrothermal replacement theory by suggesting that ascending water vapor above 650° C could deposit the sulfides and, by removal or addition of silica, convert bronzite to olivine or vice versa to produce the zoned structures and other features.

INTRODUCTION

THE property of Pacific Nickel Mines lies 7 miles northwest of the town of Hope and 100 miles east of Vancouver, at longitude 121° 30′W and latitude 49° 28′N in the rugged, wooded Coast Mountains of southern British Columbia, Canada (Fig. 1).

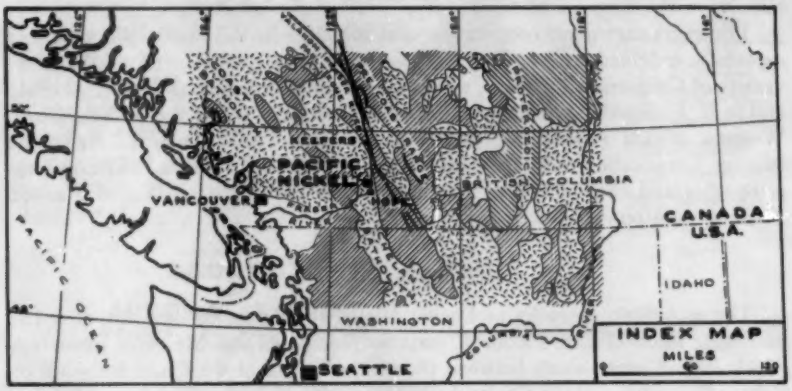

FIG. 1.

The genesis of nickeliferous pyrrhotite deposits of this general type has provoked much controversy, with theories of magmatic origin or of hydrothermal replacement origin being favored most. Such ores are all very similar to one another and are similarly closely associated with noritic, dioritic, or ultrabasic rocks. Several of the noritic or dioritic deposits have been extensively studied but, in comparison, the ultrabasic types have been somewhat neglected. Study of the geology at Pacific Nickel shows that such ultrabasic deposits can provide much new data of genetic significance.

The deposits at Pacific Nickel were discovered in 1923 and were explored until 1937, then again between 1951 and 1954. The property was briefly examined by Cairnes (5) in 1924, by Cockfield and Walker (7) in 1933, and by Horwood (20, 21) in 1936 and 1937. Cairnes concluded that the ore occurred in ultrabasic rocks that cut surrounding diorite and that it was magmatic in origin. Cockfield and Walker concluded that the ultrabasic rocks were intruded by surrounding diorite and that the ore was probably hydrothermal in origin. Horwood thought that hornblendite was the principal rock type, that the sulfide ore and pyroxenite had segregated from the hornblendite and that these were injected into their present position and then later were intruded by surrounding, genetically related diorite.

The writer studied the deposits in 1951 and 1952 and found that in large part the ultrabasic rocks apparently cut the batholithic dioritic rocks as observed by Cairnes. However, some minor dioritic differentiates do cut the ultrabasic rocks. Pyroxenite and peridotite are the main ultrabasic rocks and, contrary to earlier views, hornblendite forms only a minor proportion of the ultrabasics. The hornblendite appears to have originated largely by late magmatic reaction and replacement of the ultrabasics, not by direct crystallization from a magma. The earlier writers did not recognize that the ore occurs as elongate, steeply plunging olivine- or bronzite-rich bodies, some of which are concentrically zoned with gradational contacts, others of which are relatively massive with sharp contacts.

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REGIONAL GEOLOGY

The nickeliferous rocks at Pacific Nickel form part of the core of a 15-mile-wide block of Late Paleozoic metamorphic rocks and Mesozoic intrusives which extend north-south between the southeast end of the Coast batholith of British Columbia and the Chelan batholith of Washington (Fig. 1). Margins of this block are faulted in part against less metamorphosed volcanic and sedimentary rocks largely of Jurassic and Lower Cretaceous age (Geol. Surv. Canada, Map 737A, 1942). Serpentinites, suggestive of deep transgressive structure, occur within the block and on its east margin along faults that are southern extensions of the regional Yalakom-Fraser River fault zone. In the fall of 1954 a nickel-copper pyrrhotite deposit was discovered in a small lens of biotite diorite (of gabbroic affiliation?) in schists at Keefers, B. C., 45 miles north of Hope, along this east margin. Similar deposits might be expected elsewhere along the strike.

The nickeliferous ultrabasic rocks at Pacific Nickel form a stocklike mass about one and a half miles across (Fig. 2), bordered by a larger mass of genetically related diorites and norites, which are among the youngest of several ages of Mesozoic intrusive rocks in this area. Horwood (20, p. 2)

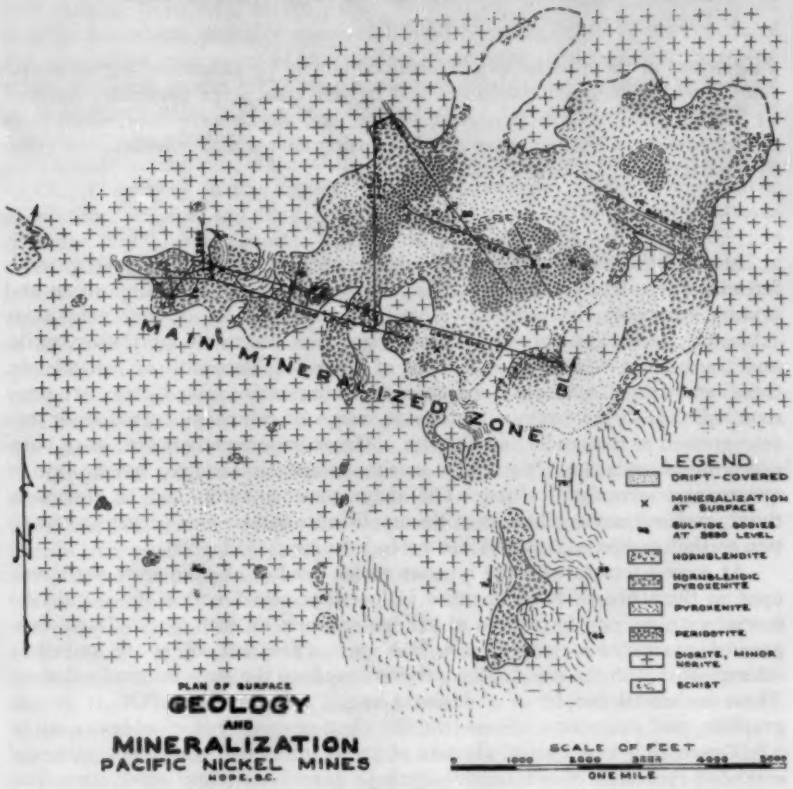

FIG. 2.

reports that the diorites cut conglomerate of probable Cretaceous age; they are grouped by the Geological Survey of Canada with other chiefly acidic intrusions that cut Upper Jurassic or Lower Cretaceous rocks. The area studied is only a part of this complex, the full extent of which is undetermined.

ROCK FORMATIONS

The following geologic units were recognized on the property (Fig. 2):

1. Metamorphic rocks, occurring south and east of the property, also represented by xenoliths in the igneous rocks (Late Paleozoic).

2. Diorites and norites, forming most of the igneous terrane; in part cut by ultrabasics, in part intermingling with them, and in minor part cutting them (Late Mesozoic).
3. Ore-bearing ultrabasic rocks—peridotite, pyroxenite, hornblendite—forming a stocklike body and smaller plugs (Late Mesozoic).
4. Dikes, veins, and alteration zones.

Plagioclase in these rocks was determined chiefly by extinction angles in sections showing centered bisectrices and by universal stage procedure outlined by Turner (34). Orthopyroxene, olivine, and augite were determined from measurements of 2V and some β indices using curves and nomenclature given by Poldervaart (32) and Hess (17).

Metamorphic Rocks

Most of the metamorphic rocks on the property are fine-grained garnetiferous quartzo-feldspathic mica schists of relatively uniform composition and texture, probably derived from silts. They consist of quartz, plagioclase (An_{29-35}), biotite and garnet, with minor graphite, magnetite, pyrrhotite, rutile, and tourmaline. Some contain bits of corroded staurolite or hornblende. Small amounts of muscovite and chlorite, retrogressive after biotite, are common. Pelitic types contain andalusite, some of which is corroded or has retrogressed to muscovite and chlorite. Minor basic members consist of blue-green hornblende ($z \wedge c = 25°$), zoisite, minor clinozoisite, sphene, minor quartz, and secondary calcite. The above rocks probably can be classed in the staurolite-kyanite subfacies of the amphibolite facies, with perhaps a transition to the cordierite-anthophyllite subfacies (35, p. 452–456).

At some contacts with the igneous rocks, needles of sillimanite are developed in the schists. A pendant or inclusion of schist within the ultrabasics contains stubby porphyroblasts of sillimanite up to an inch long. Dark, fine-grained, granoblastic-textured xenoliths up to a few feet across are intimately intermingled with the ultrabasics and diorites along the main mineralized zone. These inclusions consist of andesine (An_{35-40}), hypersthene (Of_{30}), garnet, graphite, and magnetite. Some contain cigar-shaped eyes of andesine up to a half-inch long with central clusters of green spinel that sometimes surround corroded remnants of sillimanite—perhaps pseudomorphous after corundum and cordierite. Quartz is absent in most of these inclusions but in some it forms nodules suggestive of remnants from assimilation. The above sillimanite- and hypersthene-bearing rocks are characteristic of the pyroxene hornfels facies (35, p. 441–446), believed to indicate temperatures of at least 600 or 700° C.

Diorites and Norites

Feldspathic rocks of the Pacific Nickel property are all very similar to one another in mineralogy; they typically contain less than 40 percent mafic minerals (hypersthene, augite, and hornblende), and on the basis of plagioclase composition the bulk can be classed as hypersthene- or hornblende-diorites

with minor norite phases. These rocks are medium- to fine-grained, hypidiomorphic in texture, and locally show distinct primary lineation and foliation.

Plagioclase in the diorites ranges from An_{25} to An_{50}, averaging about An_{45}. In most of the norites it averages An_{60} but ranges to An_{85} in rarer calcic varieties. Normal and oscillatory zoning are common, with composition ranging from An_{45} to An_{25} from core to rim of some sections. Small dustlike inclusions, probably exsolved hematite, concentrated in the centres of the plagioclase give many of the rocks a pink color, which is lost, however, when pyroxene in the rocks is uralitized—probably the hematite is reduced to magnetite. Minute acicular inclusions and a few small stubby prisms of apatite are also common.

Orthopyroxene ranges from Of_{20} to Of_{36} (hypersthene) in the diorites and to Of_{15} (bronzite) in the norites. Schiller inclusions, (100) clinopyroxene exsolution lamellae, and faint normal zoning (indicated by 3 to 4° outward decrease in 2V) are common. Much of the orthopyroxene is corroded; in some rocks it is rimmed by pale green, actinolitic amphibole (uralite) and in others by greenish-brown hornblende. Subordinate amounts of anhedral augite (ca. $Wo_{43}En_{44}Fs_{13}$), partly replaced by hornblende, are present in most of the rocks. Some of it forms jackets around the hypersthene. Brown to green hornblende is almost invariably present in the diorites and norites as partial or complete replacements of the pyroxene, especially augite, or as separate grains associated with the pyroxenes. Minor reddish-brown biotite is associated with the hornblende in some specimens.

Interstitial quartz commonly occurs in the dioritic rocks in amounts less than 5 to 10 percent, but in some up to 30 percent. Magnetite is present as irregular, late primary grains and as a secondary uralitization product. Pyrrhotite and chalcopyrite, rarely found in the feldspathic rocks, form xenomorphic interstitial grains.

In general, field relations of the many dioritic and noritic rock varieties are complex and criteria for age relations are commonly uncertain or lead to contradictory conclusions. The bulk of igneous rocks surrounding the ultrabasics grade imperceptibly from pink to gray diorite to norite and from quartz-free to highly quartzose types, but in several places they show various cross-cutting relations with one another. Chilled contacts are rare, suggesting a large measure of contemporaneity. In two localities, in the 512 and 1900 crosscuts of the 3550 level, pink and gray diorites cut one another and in turn appear to be cut by, and form inclusions within, adjacent ultrabasics.

The main batholithic mass of diorite appears to be cut by the main ultrabasic body. In places the dioritic rocks are cut and embayed and their lineation and foliation are truncated by the ultrabasics. At contacts with the surrounding dioritic rocks the ultrabasics show hornblendite reaction zones up to 100 yards wide. Rounded to subangular diorite inclusions of various sizes in various stages of assimilation can be seen in several hornblendic reaction zones within the ultrabasics.

Some hypersthene diorite and quartz diorite along the main mineralized zone, however, show even closer contemporaneity with the ultrabasics. Here hornblendite reaction zones are absent, dioritic apophyses extend short dis-

tances into the ultrabasics and vice versa, contacts are sharp or gradational with intermingling, and structures in the diorite and ultrabasics are concordant. Also grading into the ultrabasics are a few lenticular, discontinuous bodies of anorthositic norite a few feet or less wide, some of which form streaks and inclusions in the ore (Fig. 12).

Cutting all the other dioritic, noritic, and ultrabasic rocks are small bodies and dikes of hornblende diorite, as well as other minor differentiates (dikes and veins). These later bodies, along with cognate hornblende clots in some of the earlier diorites, may have led Cockfield and Walker (7, p. 65A) and Horwood (20, p. 5) to conclude that the main batholithic mass of diorite also cuts the ultrabasics. Horwood recognized pink diorite that was older than the ultrabasics but believed it to be Early Mesozoic in age. He thought the grey batholithic mass of diorites of Late Mesozoic age cut the ultrabasics, although genetically related to them. Many of the pink and grey diorites, however, appear to be merely color variations of the same main batholithic mass and not rocks of greatly different geologic age.

A strong genetic relation between the feldspathic and ultrabasic rocks is indicated by the close contemporaneity and intermingling, by the presence of intermediate gradations even though small in bulk, and by the presence of the same mafic minerals in the same proportions relative to one another. The various cross-cutting relations, however, suggest several successive surges of intrusion separated by enough time for partial consolidation. The feldspathic rocks and even the problems of their age relations described above are strongly analogous to those encountered in the nickel region of Sudbury, Ontario (10, 43).

Ultrabasics

Most of the ultrabasic rocks at Pacific Nickel contain no feldspar and consist essentially of fresh, undeformed bronzite, olivine, augite, and hornblende with textures that are suggestive of considerable recrystallization. In mapping, the following varieties were distinguished:

Hornblendite	Predominantly hornblende
Pyroxenite	Mainly pyroxene (commonly bronzite, with 40 percent or less augite, also minor hornblende).
Hornblendic pyroxenite	Pyroxenite with abundant hornblende, grading into hornblendite.
Bronzitite	Mainly orthopyroxene (uncommon).
Olivine pyroxenite	Pyroxenite with subordinate amounts of olivine.
Peridotite	Mainly olivine with subordinate pyroxene and minor hornblende. Hornblendic variations (common) resemble schreisheimite.
Harzburgite	Olivine and orthopyroxene.
Dunite [2]	Over 90 percent olivine.

[2] The terms "dunitic" and "dunite ore" are used for mineralized dunite where sulfide content decreases the olivine percentage to less than 90.

The grain size of these rocks varies from fine to coarse but most of the rocks are medium- to fine-grained; the texture is allotriomorphic or hypidiomorphic when dominated by olivine or pyroxene, and coarsely porphyritic or poikilitic when dominated by hornblende.

Olivine in all of these rocks, as well as in the ore, has about the same composition, Fa_{14} ($2V_x = 89° \pm 1°$). It contains small inclusions parallel to (010) and (100)—probably magnetite or chromite—which give it a dark gray to black color in hand specimens. The olivine is corroded in contact with the pyroxenes. Bronzite (Of_{10}–Of_{19}) is the major constituent of most of the pyroxenites. In some of these rocks it is jacketed by augite but the reverse relation was also observed. In some of the peridotites, subpoikilitic bronzite encloses olivine. Some of the bronzite contains small inclusions of sulfides, magnetite, or hornblende. Augite (ca. $Wo_{48}En_{47}Fs_{10}$–$Wo_{48}En_{42}Fs_{15}$), present in most of these rocks, is invariably mottled or peppered with hornblende, and partly to completely replaced by it as noted in the feldspathic rocks.

Hornblende in the ultrabasic rocks is olive-green to brown in color in thin section with $z \wedge c = 17$–$21°$ (mostly 19°) and $2V_x = 76$–$92°$ (mostly 85°). This is apparently magnesium-rich, common calciferous hornblende. In the more magnesian rocks it is paler colored with lower refractive indices and higher 2V. In reaction zones with schists or diorite it shows conspicuous brownish cores and greenish rims. In the peridotites it almost invariably forms large poikilitic grains enclosing olivine and pyroxene, whereas in pyroxenite it is rarely poikilitic but occurs as interstitial grains or as phenocrysts. The following relations show that it has formed largely, if not entirely, by reactive replacement of augite and also of orthopyroxene and olivine:

1. Augite is invariably either partly or entirely replaced by hornblende and is absent in very hornblendic rocks—it bears a reciprocal relation to hornblende.
2. Orthopyroxene and olivine are generally corroded by hornblende.
3. Hornblende has a porphyritic or poikilitic habit and is erratically distributed.
4. Hornblendites are most common as pegmatitic reaction zones next to diorite.
5. All stages of replacement and recrystallization can be traced.

Interstitial bytownite (An_{80-85}) is found in a few of the hornblendites and pyroxenites but not in the olivine-bearing rocks. Chromite forms small octahedral grains in the olivine. Magnetite is also common as inclusions in the silicates, as interstitial grains, and as an alteration by-product. Accessory interstitial sulfides and sulfide inclusions in the silicates are also widespread. Small amounts of interstitial quartz, a contamination product, were found in pyroxenite close to the schists. Alteration products common in minor amounts in the ultrabasics are phlogopite, chlorite, talc, serpentine, tremolite-actinolite, anthophyllite, and carbonates.

According to the recognized sequence of fractional crystallization in basic magmas, a sequence of magmatic crystallization that could be suggested to fit the textural and field relations in both the ultrabasic and feldspathic rocks is:

(1) chromite, magnetite (in part); (2) olivine; (3) magnesium pyroxene, joined later by magnesium-calcium pyroxene, both becoming progressively enriched in iron; (4) plagioclase, becoming progressively more sodic, and hornblende; (5) sulfides and magnetite (in part) (Fig. 5). However, as discussed later, much of the texture may have originated by replacement or conversion.

The ore-bearing ultrabasic rocks form an irregular stock-like intrusion (Fig. 2) approximately one and a half square miles in area with outcrops occurring over a range from 2,500 feet to 5,000 feet in elevation. The stock consists of cores of olivine pyroxenite or peridotite surrounded by pyroxenite, the most common rock type, which is in turn bordered by a remarkable marginal reaction zone of coarse pegmatitic hornblendite up to 100 yards wide. This remarkable type of zoning is present locally as well as on the broader scale and is characteristic of the smaller salients and even some of the orebodies. The northeast half of the ultrabasic body is barren of mineralization and contains little hornblende except at the contacts. The southwest half, however, is a "wetter," more highly varied hornblendic assemblage which is mineralized, contains all of the known ore, and in addition contains many bodies of diorite, hornblendite dikes, and various other late differentiates.

Bowen and Tuttle (4) have concluded that ultramafics apparently can be intruded only in the solid state, which should produce considerable granulation and deformation of the silicate crystals. The ultrabasics at Pacific Nickel probably were intruded as such masses of largely solid material but internal fabrics such as banding, foliation, lineation, protoclastic structure, and strained silicates are rare. The textures described suggest considerable recrystallization of the fresh silicates after any solid state movement which may have occurred.

The ultrabasic rocks are all part of one intrusion; most of their mutual internal contacts are gradational but many are also sharp. Rounded pyroxenite inclusions that occur in peridotite and in dunitic cores of the orebodies may suggest that peridotite locally cuts pyroxenite. However, in other places irregular bodies of harzburgite and bronzitite cut the peridotite, and bronzitite borders occur at some contacts between hornblendic pyroxenite and peridotite. Some contacts between pyroxenite and hornblendite or peridotite bodies are gradational in one place and planar in another, as if governed by replacement along fractures. The above features are highly suggestive of conversions from olivine to orthopyroxene and vice versa, which Bowen and Tuttle (4) found could be produced by water vapor at high temperatures (ca. 700° C).

In several localities south of the underground workings and at 2,400 feet within the 3,550 level, hornblendite can be seen in all stages of replacement of the anhydrous ultrabasics. Pyroxene cores, relict textures, contact relations, and even plagioclase content are preserved in some rocks while in others the pyroxenes have been fully replaced and the pseudomorphs and relict textures have been reconstituted to form a medium-grained, hypidiomorphic-textured hornblendite composed essentially of prismatic brown hornblende full of small magnetite inclusions. Other bodies of pegmatitic, panidiomorphic-textured hornblendite, composed of stubby hornblende crystals up to two

inches across, have apparently been formed by similar replacement but perhaps at higher temperatures. These pegmatitic hornblendites, such as those forming the reaction zone around the main ultrabasic intrusion, grade imperceptibly into the pyroxenites and peridotites at most places. All stages of replacement can be traced, yet many of the hornblendite bodies and even the hornblendic pyroxenites show lineation, sharp contacts, inclusions, contact alteration, and dike apophyses suggestive of intrusion into the surrounding, more anhydrous ultrabasics. Subpoikilitic phenocrysts of labradorite (An_{60}), labradorite-rich schlieren, and dikelike pegmatitic bodies grading into hornblende gabbro are common near inclusions and contacts of the hornblendites (Fig. 13). Such features of the hornblendites are analogous to some fabrics of the zoned orebodies and may suggest a similar origin (see hydrothermal theory of origin of the ore).

The marginal distribution of hornblendite around the ultrabasic stock suggests that constituents of the hornblende may have been derived partly from the surrounding diorites or metamorphic rocks by addition of H_2O, Ca, and Na to the ultrabasics or that the ultrabasics assimilated these rocks slightly. Indications of limited assimilation are gradational contacts, partly digested inclusions, quartz in pyroxenite near schist, quartz knots in hornfels inclusions, and rarity of contacts between peridotite and diorite or schist (pyroxenite or hornblendite usually intervenes). Intimate mixing with pyroxene-hornfels inclusions and diorites, general lack of protoclastic structure, replacement of ultrabasics by hornblendite, bronzitite veinlets, closely related dike activity, and certain features of the ore and alteration (see hydrothermal theory of origin) all suggest that the ultrabasics were emplaced at a fairly high temperature, perhaps of the order of 600 to 800° C.

Dikes, Veins and Alteration

A closely genetically related assemblage of small, aphanitic to coarse-grained dioritic or gabbroic and ultrabasic dikes cut some of the schists and all of the plutonic rocks and ore at Pacific Nickel. Many of these dikes can be traced into parent bodies that form an integral part of the exposed igneous complex. Most are less than six inches thick; a few attain a thickness of 30 inches or even 4 to 6 feet. The hornblendite dikes (Fig. 14), which are twice as common as all of the others, consist mostly of prismatic hornblende and have sharp contacts with ultrabasic wall rocks. Some consist of stubby hornblende (perhaps indicating higher temperatures) and have gradational contacts. Some cause alteration; others do not. Some contain hypersthene or bronzite phenocrysts and, rarely, serpentinized olivine with pyroxene coronas. Many grade into hornblende gabbro, and some grade into pyroxenite. The rest of the dikes vary from aplite to pyroxenite but dioritic or gabbroic types are the most common. Mafic constituents of these are brown or green hornblende, or hypersthene (Of_{20-30}), or both; rarely minor biotite or augite. The plagioclase ranges from An_{32} in aplitic types to An_{90} in very mafic types. As in the associated plutonic rocks, apatite, magnetite, and pyrrhotite are common accessories.

All the plutonic rocks and dikes are cut by numerous small veins that rarely exceed one or two inches in thickness and which consist of combinations of oligoclase (An_{15}), quartz, tourmaline, talc, calcite or dolomite; or of fine-grained carbonate with marcasite and chalcedony. These veins show no spatial relation to ore and cut across ore and veinlets of sulfides. Quartz veinlets are the most common but, except for rare pyrite and chalcopyrite, they are barren.

Uralitization is widespread, especially in the feldspathic rocks of the complex, in which much of the pyroxene is partly or completely converted to pseudomorphs. Most of these have pale green to colorless actinolitic cores, and rims of green hornblende, chlorite, biotite and magnetite. In the uralitized ultrabasics hornblende is peripherally transformed into actinolite grown in crystallographic continuity while augite is commonly completely replaced and only cores of the orthopyroxene remain. Steatitization (talc, carbonate,

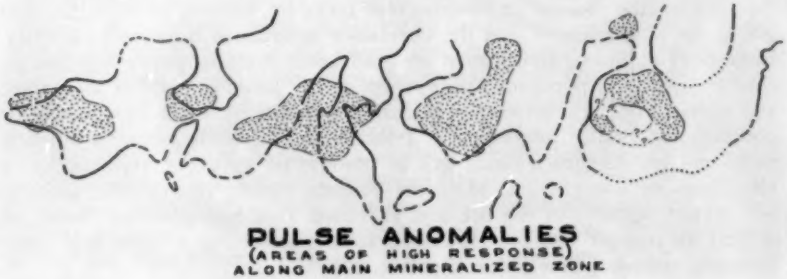

FIG. 3.

anthophyllite) affects some of the pyroxenites and locally accompanies some of the actinolitic alteration. The largest steatitized area appears to be localized along a prominent zone of shearing, uralitization, and aplite-pegmatite injection in the eastern part of the ultrabasic mass (Fig. 2). Serpentinization accompanies uralitization in some of the peridotites, some of which consist of 50 percent serpentine. Many of the remaining peridotites and olivine pyroxenites are incipiently serpentinized along cleavages and grain boundaries, and form soft, crumbly rocks (Fig. 14) which weather deeply. Poikilitic plates of phlogopite are developed in such rock in advance of this alteration, and chlorite commonly replaces the phlogopite.

All of the various types of alteration are closely controlled by, and localized along, joints, faults, dikes, and intrusive contacts and therefore could have been produced by solutions which originated elsewhere in the complex, perhaps at greater depth. Since orthopyroxene is unaffected while olivine is serpentinized, the serpentinization may be interpreted as having been produced by extraneous solutions entering the rocks below 350° C (for olivine with at least 10% fayalite) instead of by deuteric solutions (4).

STRUCTURE [3]

The main mineralized zone and the geophysical anomalies [4] all trend approximately N 75° W and plunge or dip steeply in a northerly direction parallel to internal structures in the diorite, to the internal arrangement of ultrabasic phases, and to the southwest limits of the ultrabasic stock (Figs. 2, 3, 4). This structural trend may reflect an underlying rift or shear along which igneous activity and mineralization were localized. Most of the visible fractures are clearly post-ore but some carry sulfides. In several places minor mineralization appears to be localized along zones of faulting and alteration, and along contacts between the various rock types of the steeply plunging complex. The exact control for most of the ore, however, is not yet apparent.

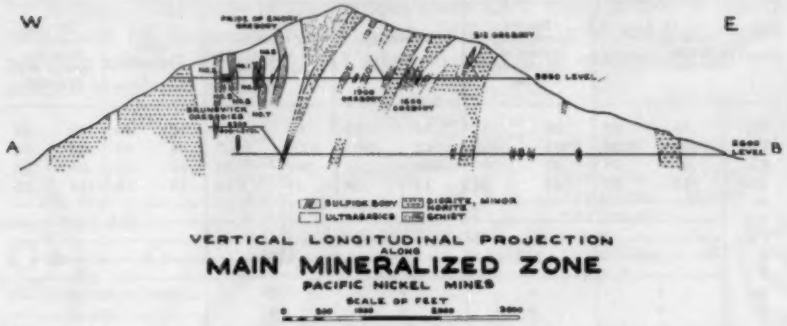

FIG. 4.

MINERALIZATION AND OREBODIES

Mineralogy and Textures

Mineralization and ore at Pacific Nickel occur almost exclusively in the ultrabasic rocks as disseminated and massive sulfides—pyrrhotite, pentlandite and chalcopyrite—interstitial to fresh undeformed olivine (Fa_{14}), orthopyroxene ($Of_{10\text{-}18}$) and, where present, augite (ca. $Wo_{42}En_{44}Fs_{13}$) and hornblende. The massive sulfides completely enclose the silicates whereas the disseminated sulfides form scattered xenomorphic grains typical of primary accessories, also poikilitic spots or rounded blebs (Fig. 15) and massive patches, many of whose boundaries truncate the enclosing silicates. In places rounded or vermicular blebs of sulfides are enclosed in bronzite (Of_{13}), hornblende, and plagioclase, but rarely in augite or olivine. These textures suggest primary magmatic origin. Minor silicate constituents in some of the ore are calcic plagioclase, and secondary actinolite, phlogopite, chlorite, serpentine, talc, and anthophyllite.

[3] A more comprehensive paper on structure of this property is to be presented in Structural Geology of Canadian Ore Deposits, A Symposium, vol. 2.

[4] The Pulse geophysical method, recently developed by Newmont Mining Corporation, measures a condenser-like discharge that is proportional to the abundance of disseminated sulfide particles in ground that has been subjected to a strong, high-voltage direct current.

Silicates.—In general, the silicates are more euhedral when enclosed completely in the sulfides than when forming barren rock, and fresh idiomorphic silicates enclosed like phenocrysts in an allotriomorphic groundmass of sulfides are more common than the earlier writers suggest (Figs. 17, 18, 19). Even fresh idiomorphic hornblende is enclosed in a groundmass of chalcopyrite in one place in the 1900 orebody. Similar textures are also common in other deposits (15, 33, 36, 40) and may suggest magmatic origin.

TABLE 1

SPECTROCHEMICAL ANALYSES

	Olivine				Orthopyroxene				Hornblende			
	Pride of Emory orebody		Barren peridotite, center of ultrabasic mass		Brunswick No. 1 orebody		Barren pyroxenite, N.E. part of ultrabasic mass		1600 Orebody		Barren hornblendite, end of 512 crosscut	
Ni	.10	.10	.08	.09	.02	.02	.03	.04	.16	.20	.07	.08
Cu	.0008	.0006	.0002	.0002	.0002	.0003	.0007	.0007	.04	.02	.02	.02
Co	.07	.08	.07	.08	.008	.01	.007	.01	.04	.04	.05	.05
Mn	.42	.48	.25	.32	.13	.14	.18	.19	.16	.16	.18	.16
Al	0.5				0.5–1.0				5			
Na	<0.1								0.5–1.0			
Ca	.005				0.5				5			
Cr	<.008		.008		0.5		0.8		0.5		0.1	
Ti	.001				0.1				0.5–1.0			
Ba	*		*		*		*		.001			
Zr	*		*		*		*		.001			
V	*		*		0.1		.05		0.1		0.1	
Mo	Tr (<.002)											
Sc	Tr								Larger Tr			
Sr	*		*		Tr		*		Tr (<.02)			
	$2V_x = 89°$ Fa_{11}		$2V_x = 89°$ Fa_{11}		$2V_x = 90°$ Of_{11}		$2V_x = 86°$ Of_{14}		Greenish $z\text{-}c = 21°$ $\gamma = 1.663$ $\beta = 1.653$ $\alpha = 1.642$ $2V_x = 92°$		Brownish $z\text{-}c = 17°$ $\gamma = 1.675$ $\beta = 1.664$ $\alpha = 1.653$ $2V_x = 89°$	

The figures above are percentages. Asterisks indicate amounts less than spectrographic sensitivity. Spectrographer, G. M. Gordon, University of California.

On the other hand, corrosion of the primary silicates is also common. Some of them have the appearance of having been partly replaced, resulting in skeletal forms that still retain plane crystal faces. Cockfield and Walker (7, p. 67A) describe replacement in various stages—from sulfides along cleavage cracks to "replacements" of interiors of crystals, and to where only isolated cleavage flakes remain unreplaced. Such corroded and embayed silicates could be explained either by selective replacement or by late magmatic reaction.

The silicates all appear essentially identical in optical and physical properties in both barren ultrabasics and in ore. Spectrochemical analyses of carefully separated duplicate samples of pure olivine, bronzite, and hornblende

showed most trace elements to be present in comparable amounts in each mineral in both barren rock and in high grade ore. Results of the analyses are shown in Table I. Only Ni, Cu, Co and Mn were determined accurately; the approximate order of magnitude of amounts of the other constituents is given. Pb, P, Sn, Li, Yt and Ag were not detected in any of the samples. The brownish variety of hornblende with the higher refractive indices is richer in iron than the greenish variety and both, having formed by reactive replacement in ultrabasics, contain more Ni and Cr than hornblende formed in a normal sequence of fractional crystallization. The variations in other trace elements are apparently of the order of magnitude that might be expected from normal magmatic differentiation or from experimental or sampling error (39).

Sulfides.—The grade of ore averages about 1.4% nickel and 0.5% copper with about 1% chromium, 0.10% cobalt, 0.02 oz/ton gold and 0.01 oz/ton platinum metals. Horwood (21) gives an average of analyses of eighteen selected samples of ore:

	Ore	Calculated to 100% sulfides		
Fe	18.38%	57.6		
S	10.87%	34.0	Pyrrhotite	ca. 75%
Ni	1.89%	5.9	Pentlandite	18–20%
Cu	0.70%	2.2	Chalcopyrite	6%
Cr	0.31%	—		
Co	0.14%	0.3	Ni/Cu	2.7
Total of sulfides:	32%			

Comparison of these figures with Table I shows that the sulfides contain about fifty times as much nickel, several thousand times as much copper, and about the same amount of cobalt as the silicates.

The sulfides themselves contain both corroded and euhedral grains of magnetite, some with cores of olivine. Rounded and corroded grains of "early" pyrite described by Horwood (20) were not seen by the writer, but pyrite was found in later hydrothermal veins and beaded stringers in the sulfides, and as replacements of pentlandite in serpentinized ore. Horwood described "early" pentlandite and a white mineral he tentatively called linnaeite. These were not seen by the writer but they may have been obtained from the stoped-out and flooded core of the 1600 orebody where the nickel content of the sulfides is 13 percent—near the limit of solubility of NiS in FeS (16). A gray mineral, which may be sphalerite, was seen by the writer in one section. Supergene minerals noted by the writer or by Horwood are limonite, chalcocite, covellite, violarite, melanterite, and morenosite.

In most polished sections whether of disseminated or of massive ore, pyrrhotite, pentlandite, and chalcopyrite are generally present in similar relative proportions and consistently show the same external relationships to silicates regardless of their mutual relations. The pyrrhotite (pale nickeliferous variety) forms a medium- to coarse-grained allotriomorphic mosaic with irregular grains of pentlandite and chalcopyrite lying between the pyrrhotite grains but rarely enclosed in them. In some specimens pentlandite and,

more rarely, chalcopyrite tend to form a discontinuous mesh between pyrrhotite grains (compare 13, Fig. 89). Chalcopyrite, present in lesser amounts than the pentlandite, more commonly forms simply bounded, isolated grains, each commonly in contact with pentlandite as well as with pyrrhotite but seldom enclosed completely in either. It also forms later cross-cutting veinlets. In some sections pentlandite is found within the pyrrhotite as minute wedge-shaped plates or blebs with flame- or fungus-like outline. These are commonly localized along walls of fractures.

Pentlandite-pyrrhotite relations similar to the above are known from almost every nickeliferous pyrrhotite deposit in the world and are accepted as being a result of exsolution from a homogeneous solid solution, not a result of replacement (13, 16). Pentlandite has been found to dissolve in pyrrhotite between 310° C and 450° C upon heating and to exsolve at about 450° C upon cooling (18). The chalcopyrite-pyrrhotite relations, which are similar,

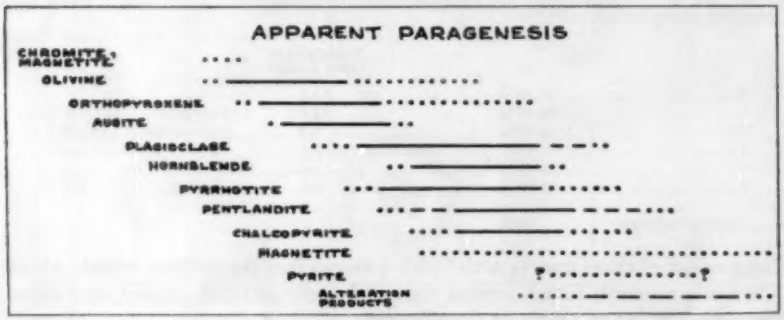

FIG. 5.

appear to be similarly explainable, at least in part. Solid solutions of pyrrhotite and chalcopyrite were obtained by Borchert (3) by heating of natural ores; by Merwin and Lombard (30) during study of the system Cu-Fe-S; and by Hewitt (18) who produced exsolution laths of chalcopyrite in pyrrhotite cooled slowly from 600° C. According to Borchert, a pyrrhotite solid solution containing about two percent copper (average for Pacific Nickel) would begin to exsolve chalcopyrrhotite at about 400° C, and by 300° C exsolution would be virtually complete. The chalcopyrrhotite would then apparently break down at about 250° C and under conditions of slow cooling (which must have prevailed at Pacific Nickel) it could apparently segregate into chalcopyrite and pyrrhotite leaving no direct evidence of its former presence. The solubility of chalcopyrite in pyrrhotite is much less than that of pentlandite; so separation of chalcopyrite would be complete while some pentlandite still remained in solid solution in the pyrrhotite. At Pacific Nickel the cross-cutting veinlets of pure chalcopyrite, however, cannot be explained by this exsolution process and must have formed after formation of the pyrrhotite solid solution. Still later, exsolution of the remaining pent-

landite along (0001) planes of the pyrrhotite would result in the flamelike exsolution growths observed in the pyrrhotite, and in the plates of pentlandite that extend into the pyrrhotite from fractures that cut chalcopyrite veinlets nearby.

In summary, for silicates and sulfides in the rocks and ores at Pacific Nickel, Figure 5 shows the indicated sequence of formation or stability of the minerals under the varying conditions of temperature, pressure and concentration of constituents. Although most of the textural evidence favors magmatic origin, this sequence could apply as well to a hydrothermal theory proposed later.

Field Relations

Disseminated Sulfides.—Disseminated mineralization is found chiefly in the "wetter" hornblendic southwest half of the main ultrabasic mass and in smaller subsidiary ultrabasic bodies to the south and southwest. The dioritic and noritic rocks are virtually barren except for some finely disseminated sulfides near a few contacts. The peridotites and olivine pyroxenites are the best mineralized of the ultrabasic rocks—most of the mineralization appears to be associated with peridotite, occurring especially near the margins of peridotite bodies. Many of the pyroxenites and hornblendic pyroxenites contain irregularly distributed, finely disseminated sulfides; but sulfides are plentiful in these rocks only adjacent to, or within orebodies, or at contacts with other rocks. The more augitic and hornblendic types are relatively barren. The widespread distribution, lack of associated alteration, lack of control by most fractures, as well as textural relations all seem to suggest that the disseminated mineralization may be a primary accessory of the ultrabasics. However, localization of sulfides near contacts (e.g. Fig. 12 and other localities) and near some fractures, particularly near bronzitite and hornblendite bodies, is equally suggestive of transportation of the sulfides, perhaps by water vapour at high temperatures as suggested earlier for origin of the bronzitite and hornblendite bodies themselves.

Ore.—The following is a 1937 company estimate of indicated ore:

ESTIMATED ORE

Type	Orebody	Tonnage	% Cu	% Ni	Ni/Cu	% Ni in sulfides
Zoned	Brunswick No. 1	165,700	0.36	1.05	2.9	4.5
	Brunswick No. 5	171,100	0.41	1.30	3.2	8.7
	Brunswick No. 6	5,400	0.77	2.08	2.7	6.6
	Brunswick No. 7	80,000	0.75	2.37	3.2	6.4
	1900	32,000	0.48	0.92	1.9	
	1600	109,000	0.36	1.20	3.3	13.0
	512	15,000	0.42	1.40	3.3	
	Trail	18,900	0.49	1.26	2.6	1.3 (?)
Massive	Brunswick No. 2	177,600	0.54	1.30	2.4	4.5
	Brunswick No. 8	4,100	0.61	1.75	2.9	
	Brunswick No. 9	2,400	0.52	1.40	2.7	
	Pride of Emory	402,300	0.57	1.49	2.6	6.6
	Total	1,183,500	0.50+Av.	1.39	2.8	

The ore occurs entirely within the ultrabasics as remarkable steeply-plunging bodies (Figs. 2 and 4), which are divisible into zoned and massive types, now described below.

1. Zoned Orebodies.—The zoned orebodies are mineralized parts of steeply plunging ultrabasic structures of circular or elliptical cross section with mineralization and rock types apparently concentrically distributed and forming somewhat cylindrical shells about the long axes of the structures. Some of these structures reach several hundred feet in diameter. The sulfide zones of several are about 100 feet across and have a plunge length of 5 to 10 times their diameter. The zoning and other characteristics described in the next few paragraphs are generally suggestive of some type of high temperature replacement origin, as discussed later under the hydrothermal theory of genesis of the rocks and ore. Table 2 is a summary of the zonal characteristics of these orebodies:

TABLE 2

Orebody	Zoning from core outward	Sulfide-rich zone	Rock surrounding the structure
Brunswick Nos. 5 and 6 (Fig. 6)	Dunite to olivine pyroxenite to barren bronzitite and bronzitic pyroxenite (bronzite, minor hornblende and augite)	Dunite core	"Common" pyroxenite (bronzite, augite, minor hornblende)
Brunswick No. 1 (Fig. 7)	Dunite to harzburgite to barren bronzitite	Dunite core and harzburgite	"Common" pyroxenite and peridotite
1600	Dunitic ore to barren hornblendic peridotite	Dunitic core	Pyroxenite and diorite
1900 (Fig. 8)	Hornblendic peridotite to bronzitite	Bronzitite ring	Augitic pyroxenite
512 (Fig. 10)	Barren olivine pyroxenite to peridotite to barren hornblendic pyroxenite to diorite	Peridotite ring	Hornblendic pyroxenite

Table 2 shows that the sulfides are, as a rule, concentrated in the olivine-rich parts of the orebodies, the only exception being the 1900 orebody where the peridotite is not as well mineralized as the surrounding bronzitite. Some of the orebodies show concentric distribution of mineralization around a peridotitic core and one, the 512, contains pyroxenite inside the peridotitic zone. The cores of most of these structures consist of dunite or peridotite containing disseminated to massive sulfides which enclose a gangue of corroded or idiomorphic olivine (Fa_{14}). The olivine tends to be coarser where sulfides are most abundant; for example, the dunitic core of the 1600 orebody is coarser grained and higher in grade than that of any of the other orebodies —it contains olivine up to a quarter-inch across and averages 5% Ni and 1.2% Cu. The cores also contain schlieren, patches, or dikelike bodies of more

massive sulfides, and local rounded or irregular pyroxenite inclusions which are rimmed in places by massive sulfides. In these characteristics the fabric of the dunitic ores is strikingly similar to the fabric of some of the hornblendite replacement bodies described earlier; that is, if the olivine is compared to the hornblende and the sulfides are compared to the calcic plagioclase.

With lesser amounts of olivine the dunitic or peridotitic cores grade outward into zones of either harzburgite or olivine pyroxenite and into bronzitite. Contacts between these zones within the ore-bearing structures are generally gradational but in places they are sharp. The outer fringes or rocky sections of the orebodies have a higher proportion of chalcopyrite (lower Ni/Cu ratio) and are more erratically and poorly mineralized, commonly with blebs or irregular patches of sulfides or with veinlets of chalcopyrite. Similar relations have been noted in other nickel deposits (11, p. 619; 14; 31, p. 79; 33, p. 198;

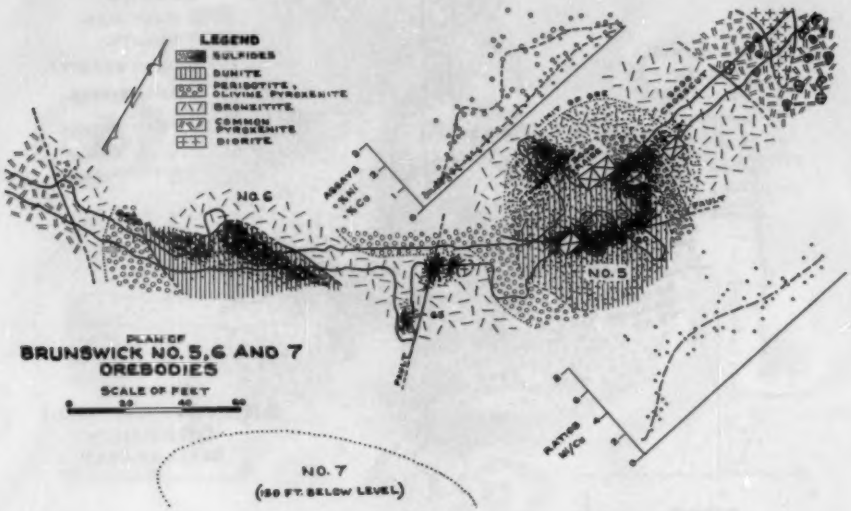

FIG. 6.

37, and others). These accounts describe chalcopyrite as being variable in amount, always associated with the other sulfides, but proportionately more abundant in margins or rocky parts of orebodies, and extending out into the country rocks. The writer has also observed similar relations in several other nickel deposits in Yukon Territory, Canada. As seen from the table of estimated ore, the ratio of nickel to copper averages about 2.8. It and the percentage of nickel in the sulfides are highest in dunite (e.g. in Brunswick No. 5 and No. 6 orebodies) and lowest in erratically mineralized hornblendic rocks (e.g. 1900 orebody). This variation is shown even in individual orebodies, especially Brunswick No. 5 where the Ni/Cu ratio is about 4 in the dunite core and about 2.5 in olivine pyroxenite and bronzitite on the north

side of the orebody (Fig. 6). Elsewhere on the property minor mineralization localized near fractures, contacts, or hornblendite bodies was found to have the lowest nickel content. The above distribution of sulfides and textures seems too varied to be entirely magmatic in origin.

Most of the ore-bearing rocks of the zoned structures also differ in composition, texture, and color from the surrounding ultrabasics—they are more magnesian, and contain more olivine and bronzite, and commonly less augite

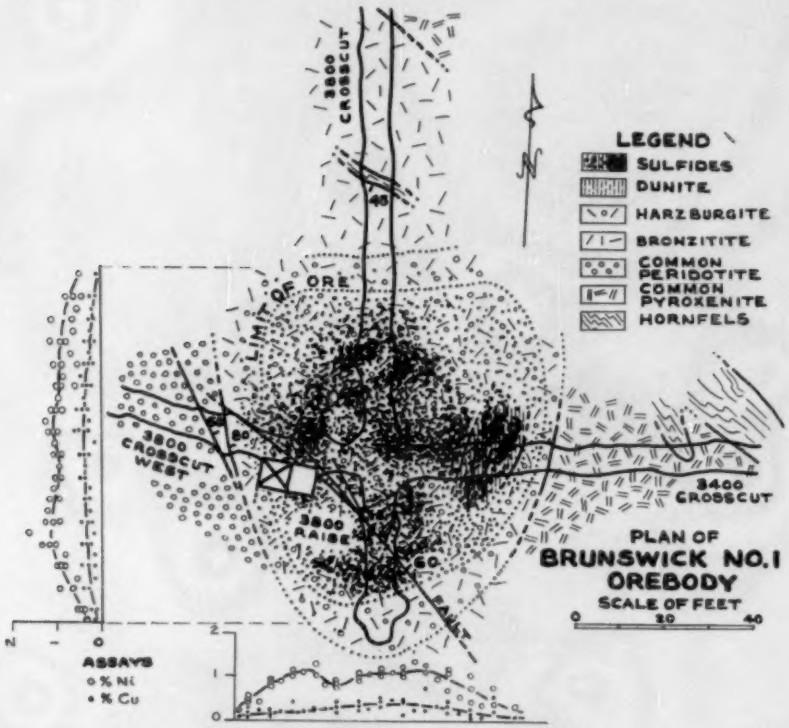

FIG. 7.

or hornblende than the surrounding rocks. For example, augite and hornblende are minor or absent in the Brunswick and Pride of Emory group of orebodies but the wall rocks contain various amounts of these minerals. In the 1900 orebody hornblende is abundant but augite is absent even though the surrounding rock contains 60 percent augite. It might be argued here that these sulfide- and magnesium-rich bodies are early magmatic differentiates injected from depth after segregation and that the zoning resulted from successive injections up the same channelway.

The most complex, zoned structures are illustrated by the 1900 and 512 orebodies, described below in detail:

The 1900 orebody (Fig. 8) has a medium- to coarse-grained hornblende peridotite core consisting of olivine (ca. Fa_{14}), bronzite (Of_{16}), and poikilitic hornblende in nearly equal proportions. Aligned blebs of sulfides (Fig. 15) are disseminated in parts of this core. Surrounding the core is a zone of medium-grained bronzitite (Of_{16}) containing concentrically distributed barren hornblendite schlieren, erratically mineralized bronzitite with interstitial sul-

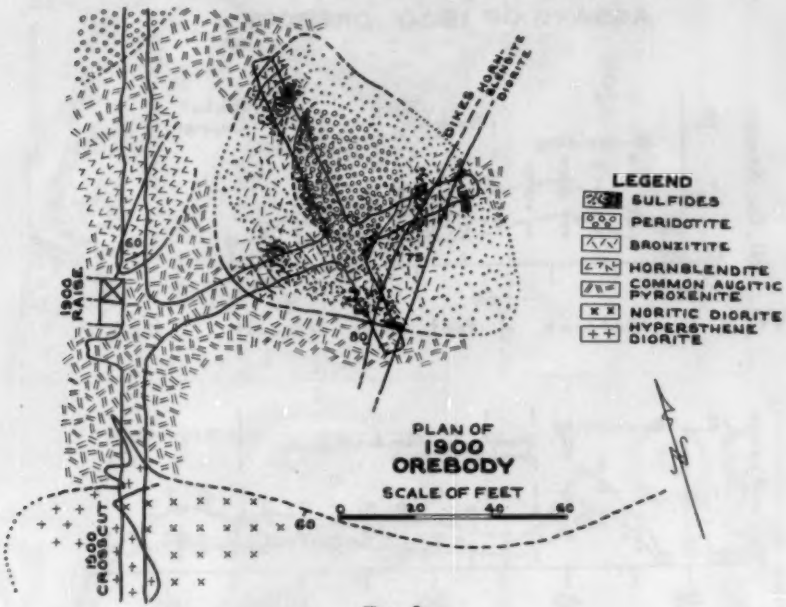

FIG. 8.

fides, and barren porphyritic hornblende bronzitite with hornblende phenocrysts. Interstitial labradorite is locally present in the bronzitite and in the coarser hornblendic schlieren. Some of the ore shows "protoclastic structure" (Fig. 16). Mapping shows a concentric arrangement of mineralization corresponding to the bronzitite zone; and assays (Fig. 9) show this zonal arrangement well. Bronzitite and hornblendite at the outer edge grade within inches into completely barren, surrounding, hornblende-speckled augitic pyroxenite (60% augite (ca. $Wo_{43}En_{44}Fs_{13}$), 25% bronzite (Of_{16}), 15% hornblende). Eight thin sections from various parts of the orebody itself showed no augite. Several hornblendite dikes and dioritic dikes cut the orebody. The 1900 orebody is more complex, lower in grade, lower in ratio of nickel to copper, and more hornblendic than the others, and is more suggestive of replacement origin.

The 512 orebody is a striking example of what appears to be a steeply plunging troughlike body of ore in a westerly plunging zoned structure (Fig. 10). Here, a central body of barren olivine-bearing hornblendic pyroxenite is surrounded in turn by an arc of mineralized olivine pyroxenite, a shell of barren hornblendic pyroxenite and hornblendite, a shell of barren diorite, and finally by barren, enclosing, hornblendite or hornblendic pyroxenite. The mineralization exposed in the raise and on the surface consists of blebby and interstitial sulfides in the footwall side of the olivine pyroxenite zone. The

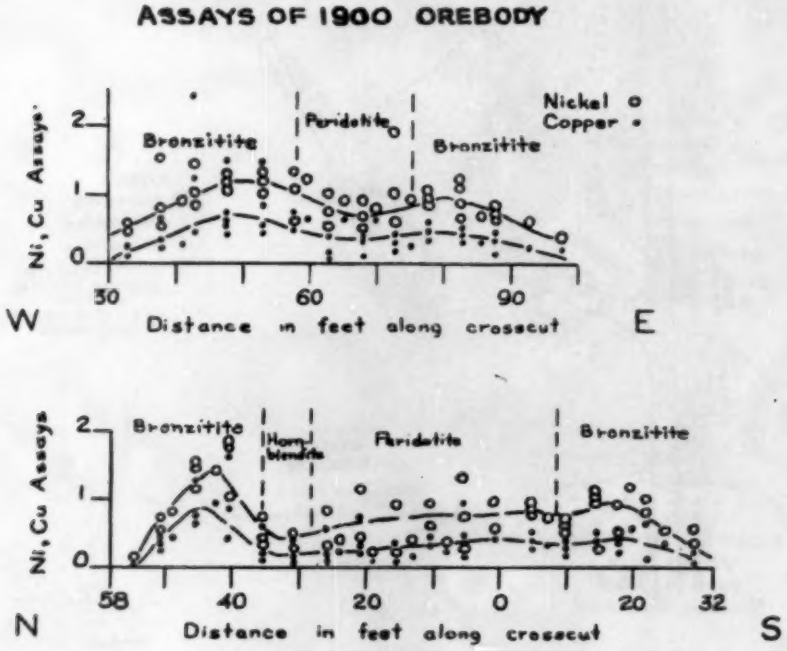

FIG. 9.

ultrabasics appear to cut the diorite in the adjacent 512 crosscut. Although the general characteristics of the other zoned orebodies may suggest some type of replacement origin, this zoning of the 512 orebody seems difficult to explain simply by any theory of origin except perhaps by injection into the diorite shell followed by replacement.

2. Massive Orebodies.[8]—The "massive" orebodies are similar to the zoned type in size, attitude, mineralogy, and many other characteristics but they are much more suggestive of magmatic sulfide injections rather than hydrothermal replacements. They are more irregular in cross section and

[8] The term "massive" is used here to imply massive structure.

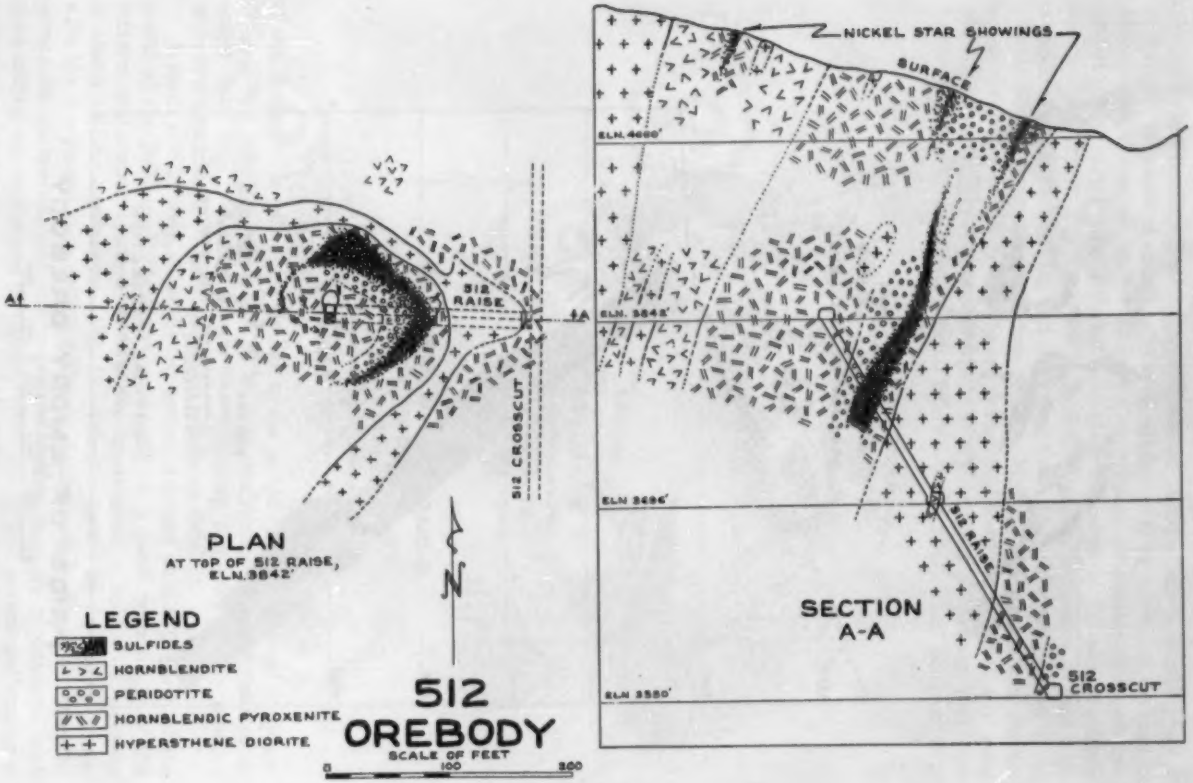
NICKEL STAR SHOWINGS
SURFACE
ELN. 4000'
ELN. 3848'
ELN. 3696'
ELN. 3550'
512 RAISE
512 CROSSCUT
A
A
PLAN
AT TOP OF 512 RAISE, ELN. 3842'
SECTION A-A
LEGEND
SULFIDES
HORNBLENDITE
PERIDOTITE
HORNBLENDIC PYROXENITE
HYPERSTHENE DIORITE
512 OREBODY
SCALE OF FEET
0
100
200

FIG. 10.

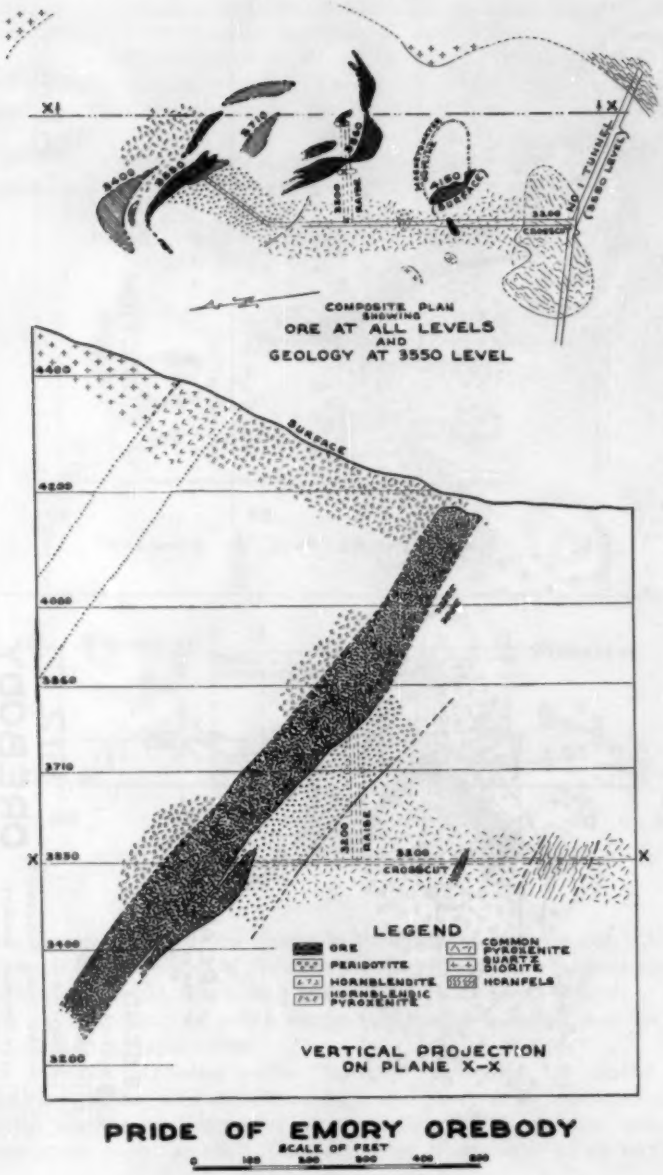
COMPOSITE PLAN SHOWING
ORE AT ALL LEVELS
AND
GEOLOGY AT 3550 LEVEL
SURFACE
4200
4000
3860
3710
3550
3400
3200
RAISE
CROSSCUT
LEGEND
ORE
PERIDOTITE
HORNBLENDITE
HORNBLENDIC PYROXENITE
COMMON PYROXENITE
QUARTZ DIORITE
HORNFELS
VERTICAL PROJECTION
ON PLANE X-X
PRIDE OF EMORY OREBODY
SCALE OF FEET

FIG. 11.

consist rather uniformly of a groundmass of sulfides which contains up to 50 percent or more of evenly scattered idiomorphic or corroded crystals of bronzite or olivine or both. The type or relative proportion of these two silicates may vary in the different orebodies and even in the same orebody. Zonal arrangement, if present, was not seen. Locally, inclusions of wall rock, marginal flow lines, banding, and even drag folds (Fig. 17) are present in the "massive" ore, suggesting injection origin. Many of the contacts of the ore are as sharp as a pencil line, some are gradational over a few inches, and some show local hornblendic reaction rims. The wall rocks vary from peridotite to norite and show no apparent zonal relation to the ore. The "massive" type

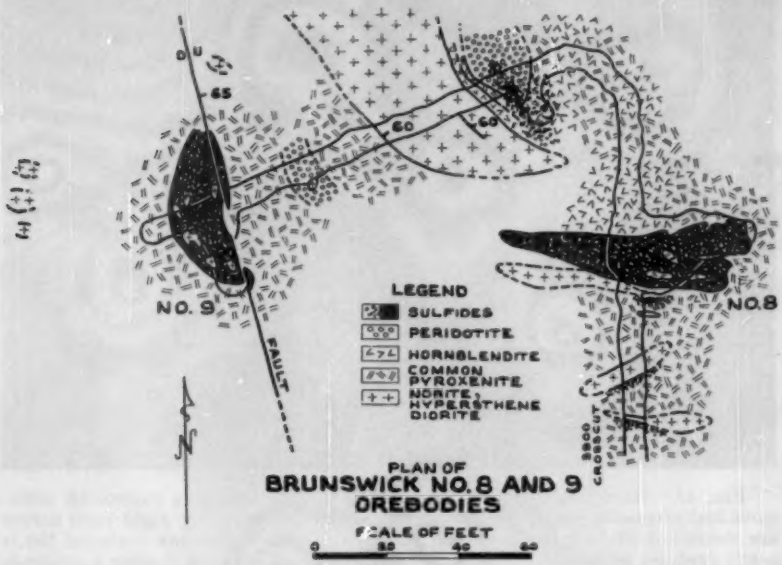

FIG. 12.

of ore, however, is otherwise similar to the zoned type; moreover, it apparently grades into the zoned type in at least two orebodies so any theory of origin must apply to both types. The following examples of the massive orebodies illustrate their general features in more detail:

A small sulfide body about 10 feet across, exposed on a cliff north of the portal of the 2600 level, illustrates admirably on a small scale many of the textures and contact characteristics of the larger massive bodies. It consists of coarse sulfidic harzburgite (Fig. 18) (similar to ore of the zoned Brunswick No. 1 orebody) with sulfidic schlieren, concentrations of olivine, rounded pyroxenite inclusions, and coarse-grained sulfide borders at contacts with surrounding pyroxenite and peridotite, which are largely barren and unaltered except near fractures.

Brunswick No. 2 orebody, although similar in size, attitude, and known extent to the zoned Brunswick No. 1 orebody and associated with a similar mass of bronzitite, is irregular in cross section and has sharp contacts. The ore consists of subhedral bronzite and clots or large crystals of olivine enclosed in a sulfide groundmass. It is separated from surrounding peridotite by a shell of pyroxenite 2 to 4 feet thick. Lenses of bronzitite and harzburgite occur in and near the ore. Silicate clots in the ore are crudely lineated.

FIG. 13. Hornblendite at 1600 crosscut, 3550 level, showing pyroxenite inclusions and plagioclase-rich "segregations." Inclusions in the top right hand corner are steatitized whereas the large inclusion by the hammer appears unaltered but is partly replaced by hornblendite. Many of the white specks are shining hornblende cleavages, not plagioclase grains.

The Pride of Emory orebody (Fig. 11) consists of several elongate bodies, perhaps anastomosing, which were traced for about 900 feet from the surface with little change in bulk. At the surface and in the 3200 raise the ore forms massive lenses with a fresh medium-grained bronzite (Of_{14}) gangue in a sulfide groundmass. This ore shows sharp contacts and flow lines. On the 3550 level the ore consists largely of medium-grained dunite with interstitial sulfides between fresh subhedral olivine (Fa_{14}), identical to dunite ore of the zoned orebodies. On the west this dunite ore grades into relatively barren peridotite, on the south it grades into a border zone of bronzitite ore, and on the east it is in sharp contact with hornblendic pyroxenite. Small irregular stringers, massive coarse-grained blobs, and disseminated grains and blebs of sulfides extend a couple of feet outward from the sharp eastern contact.

One block of ore, believed to have come from this contact, shows drag-folding of banding parallel to a contact between dunite ore and barren pyroxenite (Fig. 17).

Brunswick No. 8 and No. 9 orebodies (Fig. 12) are identical to one another and consist of fine- to medium-grained, fresh, euhedral bronzite (ca. Of_{18}) in a groundmass of sulfides, parts of which have a delicately interlacing network of thin chalcopyrite stringers. Minor constituents of the ore are hornblende, bytownite (An_{80}) and local alteration products. Both orebodies contain rounded or irregularly shaped anorthositic norite streaks and inclu-

FIG. 14. Hornblendite dikes cutting crumbly altered peridotite in 512 crosscut, 3550 level.

sions from an inch to two feet or more across. Some of these inclusions are drawn out into streaks and lenses which, if seen alone or on one surface, might be interpreted as norite cutting ore (see Horwood's statement (20, p. 14) that ". . . sulfide bodies have been intruded by irregular tongues and bodies of diorite"). In places, sulfide-impregnated reaction rims up to two inches thick, composed of hornblende with minor spinel and sulfides, separate the ore from the barren norite inclusions or from surrounding pyroxenite. The sulfides in most places do not penetrate far into the wall rocks and many of the contacts of these two orebodies are as sharp as a pencil line.

Veinlike Mineralization.—Many beaded stringers or veinlets of sulfides from a fraction of a millimeter to two inches in width occur within or near

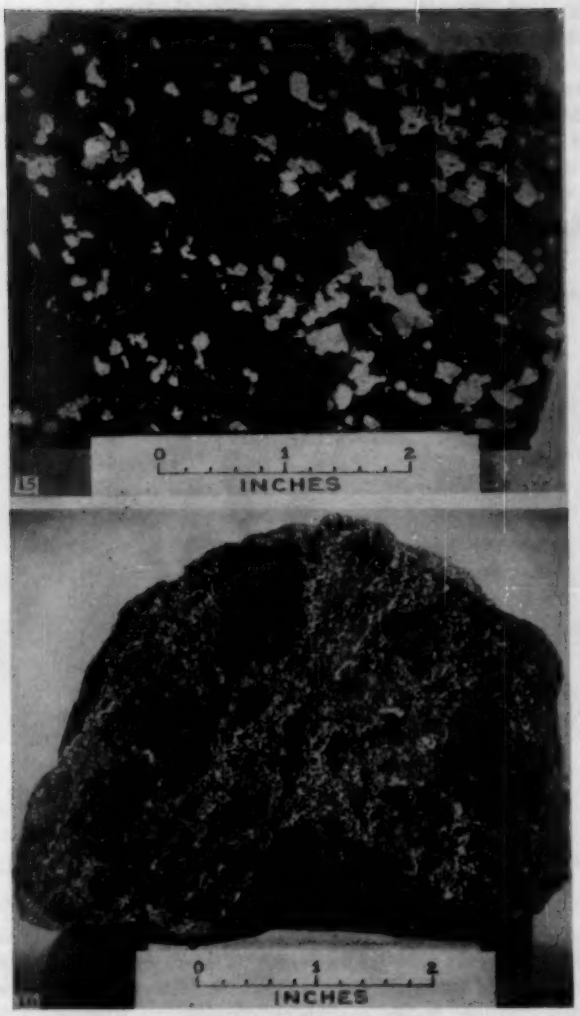

FIG. 15. Typical blebby disseminated ore in hornblendic olivine pyroxenite, core of 1900 orebody, showing aligned sulfide blebs (white). The silicates are fresh olivine, bronzite and hornblende in equal amounts and the blebs are chiefly pyrrhotite with minor pentlandite and chalcopyrite. Some of the blebs consist entirely of chalcopyrite.

FIG. 16. "Protoclastic" structure in hornblendic bronzitite with stringer-like interstitial network of chalcopyrite (white). From 1900 orebody.

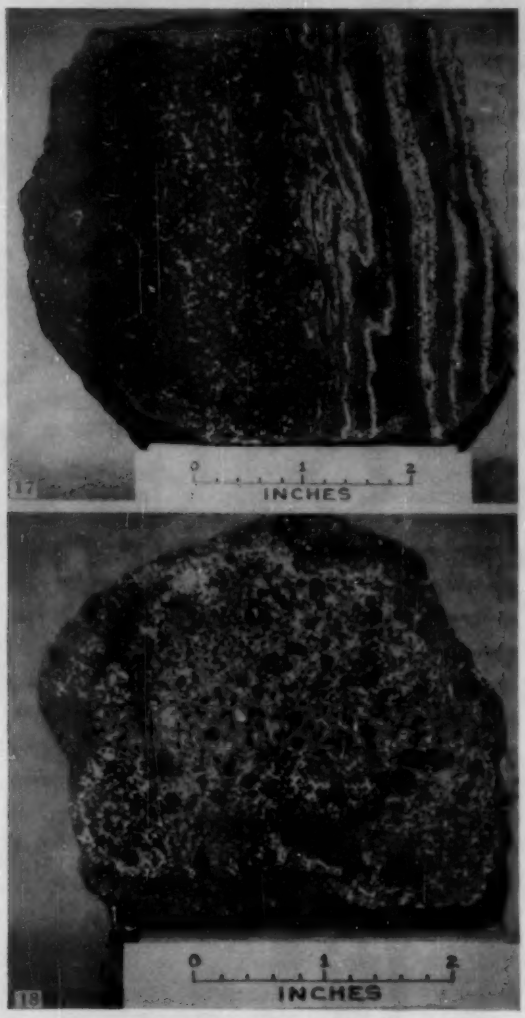

FIG. 17. Lineation and drag-folded marginal sulfide bands at contact between dunite ore (left) and barren pyroxenite (right, broken off). Note the euhedral olivine in the faintly banded dunite ore. The dark bands on the right are pyroxenite with pyroxene lineated parallel to the banding. Probably from northeast contact of Pride of Emory orebody.

FIG. 18. Typical harzburgite ore. The large euhedral crystals are mainly bronzite and the smaller crystals and clots are mainly olivine. The groundmass consists of coarse-grained pyrrhotite with pentlandite (shining cleavages) and minor chalcopyrite. From small massive sulfide body north of portal of 2600 level.

most of the orebodies and to a lesser extent in the surrounding rocks. These veinlets are commonly rich in chalcopyrite but some consist mainly of pyrrhotite which may impregnate the wall rocks up to distances of two inches. In the orebodies most of these veinlets cut the other sulfides but in many places they intermingle and cut only the silicates. They display the same degree of corrosion or replacement as observed in the ore. Some appear to be simple infillings with matching walls. Others show altered walls and from still others irregular patches of sulfides extend into unaltered wall rocks, similar to relations shown by Cameron (6) from Mount Prospect, Connecticut. At Pacific Nickel the lack of such sulfides in most of the later veins and alteration fractures, some of which cut these sulfide veinlets, suggests that the veinlets are a late dying phase of the main sulfide mineralization whether magmatic or hydrothermal, and not later mineralization "related to the diorite" as believed by Horwood (20, p. 12).

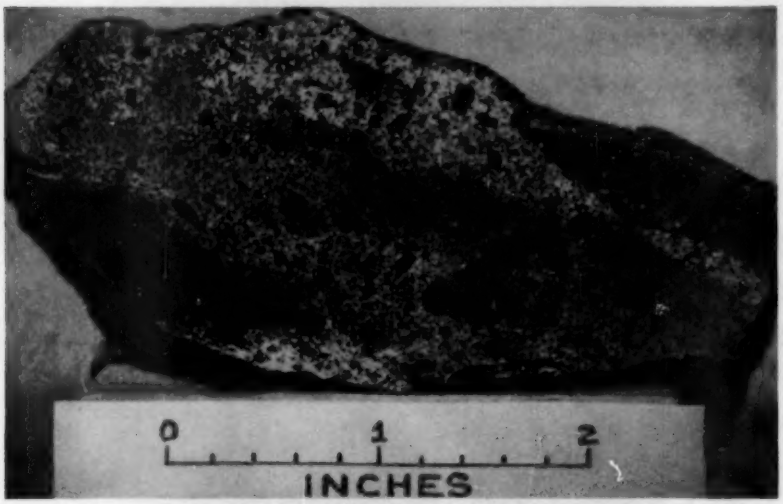

FIG. 19. Section of 2-inch-wide hornblende-pyrrhotite "dike" or "vein" showing euhedral hornblende, an inclusion of pyroxenite altered to actinolite, and hornblenditic margins. The pyrrhotite (light) carries minor chalcopyrite and small exsolution laths of pentlandite. This "dike" cuts olivine pyroxenite and grades visibly into a hornblendite dike. From 1,250 feet within 512 crosscut, 3550 level.

Lenticular, discontinuous, heavily mineralized, medium- to fine-grained pyroxenite and hornblendite "dikes" a few inches to a foot wide cut peridotite 1,300 feet within the 3550 level and 1,250 feet within the 512 crosscut. The pyroxenite dikes locally grade into the hornblendite dikes; sulfides within both are unevenly distributed and tend to be concentrated into massive blobs that extend irregularly like replacements into unaltered wall rocks. These sulfides are chiefly pyrrhotite, with smaller amounts of nickel and copper than sulfides

in the orebodies. In places the "dikes" grade into massive sulfide "veins" or lenses that carry scattered idiomorphic crystals of hornblende (Fig. 19). Flow lineation and altered wall rock inclusions were found in one such "vein." The surrounding pyroxenite and peridotite are mineralized and locally altered, especially along fractures. Bands of sulfides an inch or two wide and similar to the above lenses occur in a few localities in pyroxenite and in hornblendite elsewhere on the property. Although the above tabular sulfide bodies might be attributed to high temperature pneumatolysis, their characteristics seem equally suggestive of injection accompanied by replacement. In either case the relations indicate close contemporaneity of the early pyroxenite-hornblendite dikes and the late stage of mineralization. Hornblendite dikes similar to the sulfidic ones clearly cut some of the ore bodies but these dikes contain only thin stringers and local impregnations of sulfides, which could be explained by reactivation of sulfides by the dikes.

Now that the sulfide bodies and their environment have been described, one is confronted with the problem of genesis. However, since the theories of genesis that are to be presented may apply to other similar nickel deposits as well, the significant genetic characteristics of other deposits in the world are first summarized and compared with those of Pacific Nickel, then the theories of genesis are discussed.

GENESIS OF THE ROCKS AND ORES

Genetic Comparisons

In the layered norite-ultrabasic complexes such as the Bushveld complex of South Africa (40), the complexes of Griqualand and Pondoland (33), the Petsamo complex of Finland (15), and the Stillwater complex of Montana (23), sulfides are generally concentrated in basic or ultrabasic horizons and this concentration may be explained by simple gravity segregation followed in some cases by minor movement which would give rise to cross-cutting relations. Wagner has expressed the view that it is inconceivable that vagrant solutions could have selectively impregnated extensive layers of such lopoliths with sulfides.

Many of the other nickel deposits of the world are found chiefly within or marginal to noritic rocks, notably in the more basic and varied portions or near pendants or inclusions (1, 6, 12, 24, 36, 37, and others). A lesser number, often smaller but richer in nickel, occur within or marginal to ultrabasic bodies (25, 29, 38, and others). A few "offset" deposits occur along tectonic breaks near the parent intrusives (14, 36). Evidence has been cited from some of the above deposits that favors gravity segregation of sulfides with or without subsequent injection. From others (especially some of the complex offset types) much evidence is cited for hydrothermal origin. Most of the deposits, however, are still noted for general lack of hydrothermal alteration associated with the ore. (This is also true for many pyrometasomatic deposits formed above the temperatures of the more common alteration products). No concentric zoning is described even in the ultrabasic deposits, which are otherwise very similar to those at Pacific Nickel.

Compared with Pacific Nickel, the Canadian nickel region of Sudbury, Ontario, which has been most extensively studied, has the same petrologic association of feldspathic rocks with ambiguous age relations, the same type of ore and alteration, with the same general evidence of high temperature, lack of widespread alteration, close relation to magmatic activity, "magmatic" textures and mineralogy with minor replacement, high copper at margins of ore, sharp and gradational contacts, "suspended" inclusions, and hornblendic reaction rims between massive ore and country rocks. In contrast to Pacific Nickel, the deposits of Sudbury contain micropegmatite or potash feldspar, occur in quartz diorite host rocks, contain no ultrabasics and little or no olivine or pyroxene, are controlled more by tectonic breaks, and apparently show more evidence of hydrothermal action, replacement, reconstitution of rocks, and impregnation by sulfides. The offset deposits, particularly, show greater complexity, richness, concentration of rarer constituents, and more hydrothermal action. Many characteristics of the deposits at Sudbury led Coleman (8) and Howe (22) to suggest sulfide segregation and injection, and Bateman (2) and Collins (9) to suggest injection accompanied by extensive hydrothermal modification and redistribution. Further study, however, has led Davidson (11) and Yates (43) to conclude that the deposits are hydrothermal in origin. The columnar offset orebodies of Sudbury are strikingly similar in size, shape, and attitude to some of the orebodies of Pacific Nickel. Coleman (8, pp. 36–37) reported that "the Copper Cliff deposit was known to go down for 1,000 feet without interruption as a rude oval pipe with diameters varying from 50 to 200 feet, and a dip of 77½ degrees to the northeast." The two orebodies of the Victoria mine are similarly described as ". . . two small cylinders of ore, more than 1,400 feet in length and close together, but never meeting . . ." (compare with Pride of Emory orebody).

A nickel-copper deposit at Funter Bay,[6] 18 miles west of Juneau, Alaska, is also somewhat similar to the elongate, steeply plunging orebodies at Pacific Nickel, and probably similar to the small mineralized ultrabasic bodies a mile to the southwest. Surrounded by schist and phyllite, this deposit is an almost cylindrical mineralized gabbro plug or pipe about 100 feet in diameter, which has been followed for 600 feet down a moderate southeast plunge. The best mineralization lies along the lower contact of the plug, near the crest of a complex fold in the adjacent schists and phyllites. This mineralization consists of a massive body of several hundred tons of sulfides assaying up to 4% Ni and 6% Cu. Low-grade mineralization consisting of pyrrhotite, chalcopyrite, and minor pentlandite, is scattered in the gabbro as disseminated interstitial grains, as round or elongate blebs up to an inch across, and as patches and veinlets some of which cut or partly replace acidic dikes in the gabbro. The sulfides also extend a few feet into a 40-foot-wide cordierite hornfels metamorphic aureole which apparently surrounds the gabbro. In some places in the gabbro as well as in the hornfels, the sulfide blebs are generally oriented, commonly with curious chalcopyrite rims that thicken in one particular direction. Carbonate blebs of similar size and shape, with

[6] Personal communication with J. J. McDougall, St. Eugene Mining Corporation.

rims of talc, are locally associated with these sulfide blebs. The disseminated sulfides were thought to be magmatic in origin whereas the blebs, patches, and veinlets were thought to represent extension of the same mineralization into a hydrothermal phase.

At the south end of Tagish Lake in northern British Columbia, Canada, the writer saw a small gabbro-ultrabasic complex locally mineralized with pyrrhotite and chalcopyrite, especially in its more ultrabasic phases. One partly altered pyroxenitic area contains a sharply bounded, six-foot-diameter sulfide body consisting of about 50 percent of medium to coarse subhedral hornblende in a pyrrhotite matrix, producing a texture similar to that shown in Figure 19. The pyrrhotite contains blebs, stringers, and patches of chalcopyrite and, under the microscope, small exsolution laths of the pale nickeliferous phase of pyrrhotite. The chalcopyrite is erratically distributed and favors margins or rocky parts of the sulfide body. The mineralization averages 0.56% Ni and 0.8% Cu.

In association with peridotite and hornblendic pyroxenite at Bruce Lake, southeast of Ross River Post in Yukon Territory, Canada, the writer saw float of olivine-pyrrhotite rock which carried only traces of copper and nickel but was otherwise identical in appearance to the dunite ore at Pacific Nickel.

In the Kluane Range of Yukon Territory, nickel-copper sulfide mineralization is localized at contacts of gabbro and peridotite bodies; for example, at the Wellgreen property presently being explored by Hudson Bay Exploration and Development Company. On this property lenses of ore are localized where a dioritic phase is found along the contact of a peridotite body. A careful detailed study of this deposit may provide a valuable link between knowledge on deposits such as Sudbury on the one hand and Pacific Nickel on the other.

Some zoned cylindrical- and funnel-shaped ultrabasic complexes in southeastern Alaska (26, 27, 42) are very similar in zoning to the stocklike ultrabasic body at Pacific Nickel. These complexes are hundreds or thousands of feet across, and have peridotitic cores surrounded successively by pyroxenitic and gabbroic or hornblenditic rocks. Walton (42) suggests that the zoning originated by gaseous and ionic transfer.

The platiniferous dunite pipes of the Bushveld igneous complex of South Africa (41) show zoning most similar to that of the orebodies at Pacific Nickel. These pipes, up to 200 feet in diameter, have a core of hortonolite dunite surrounded by olivine dunite, wehrlite, and other less olivine-rich rocks, all of which cut across layering of the surrounding complex. They also contain chromitite xenoliths (ibid., p. 68) and "boulder-like inclusions of anorthositic norite" (ibid., p. 72) apparently derived from the surrounding complex and displaced slightly (compare with inclusions in ore at Pacific Nickel). In contrast to the zoned structures at Pacific Nickel these pipes contain a more iron-rich olivine and lack sulfides. They were believed by Wagner to be pneumatolytic although inclusions, sharp contacts, and displacement of the chromitite inclusions also suggest minor movement.

Most strikingly similar in character to the deposits of Pacific Nickel are the sulfidic harzburgite pipes of Vlackfontein, 4,000 feet above the base of the

same Bushveld igneous complex (19, 40). These deposits are equally well developed in bronzitic norite, bronzitite, and harzburgite of the complex and cut across and replace flatly dipping layers of these rocks. The pipelike bodies are gradationally as well as sharply bounded, steeply plunging, and from a few feet to 70 feet across and several hundred feet long; they commonly show disseminated ore toward the periphery and more massive sulfides near the centre. Basic dikes that cut the bronzitite and harzburgite are displaced and partly replaced by the sulfides indicating ". . . that the ore was introduced after the bronzitite and harzburgite had sufficiently cooled and crystallized to permit the dike to intrude them and preserve its identity" (19, pp. 209–210). Hoffman ruled out pneumatolytic origin because of lack of "typical" pneumatolytic minerals, but left the impression that the ore may have formed by some replacement process, perhaps accompanied by some movement. No zoning is described.

The above genetic comparisons show that pipe- or parsnip-like shapes and zonal characteristics occur in other similar rocks and ores in the world and may be much more common than previously recognized. With these occurrences, and their characteristics, similarities, and proposed origins in mind, theories of origin of the ore at Pacific Nickel may now be considered.

The Magmatic Theory

The mineralogy, fabric, and occurrence of the igneous rocks and ore at Pacific Nickel could be explained well by a theory of fractional crystallization and gravitative differentiation followed by injection. During fractional crystallization of a basic parent magma, silicate crystals and immiscible sulfide melt could settle to the bottom of the magma chamber to form sulfidic olivine-rich layers which could then be buried in turn by pyroxenitic, noritic and dioritic layers. Then, beginning with the overlying diorite and followed by ultrabasics and ore, the layered differentiates could have been injected into the roof of the magma chamber to give the present field relations and sequence. Presence of sulfides in the ultrabasics and their scarcity in the norites and diorites would substantiate such a theory of early sulfide segregation from a still fluid magma into a compacted, early-formed ultrabasic crystal mush at the bottom of the magma chamber. Blebs of sulfides are found totally enclosed in bronzite (Of_{18}) in pyroxenite—this might also indicate immiscible segregation during early stages of fractional crystallization, as suggested by Vogt (36).

The textures, lack of alteration, and gradation of ore into widely disseminated, apparently primary sulfides do suggest magmatic origin of the ore particularly since it occurs in the most magnesian of the ultrabasics. Even the corrosion, replacement, sulfide veinlets, and minor alteration observed in places can be explained by a magmatic theory assuming some redistribution. The steeply plunging orebodies, however, could not be explained by simple magmatic gravity segregation; but segregation followed by injection would account admirably for their attitude and for the signs of movement such as

sharp contacts, flow lines, drag folds in marginal sulfide bands, wall rock inclusions, and dikelike sulfide bodies. Even the zoning might be explained by successive injections. Characteristics suggestive of intrusive origin found in other nickel deposits led Vogt (36), Howe (22), Bateman (2), Collins (9), and others to conclude that such ores were indeed molten sulfide injections. But the sulfides at Pacific Nickel, if injected, could not have been entirely molten; otherwise inclusions and silicates would have floated and schlieren, lineation, and drag folds would have been destroyed. The larger scale "protoclastic" textures of some of the ore are suggestive of movement in a largely solid state but microscopic textural evidence of such is lacking in general, except possibly in the crystallographic fabric orientation of the sulfides. Any textural evidence of such a fabric, if it existed, may have been obliterated by recrystallization, minor hydrothermal redistribution, and exsolution.

Since pyrrhotite begins to crystallize at rather high temperatures, the sulfide bodies, if injected, probably were largely crystalline. Hawley, Colgrove, and Zurbrigg (16) show that in a simple anhydrous Fe-Ni-S melt containing about 6 percent nickel (average for Pacific Nickel), FeS would begin to crystallize at about 1150° C; and at about 870° C these early formed crystals would probably enter into a peritectic reaction with the residual nickel-enriched liquid to give a pyrrhotite solid solution which, upon cooling below 400° C, would exsolve pentlandite. Two or three percent copper would probably lower the initial crystallization temperature of simple pyrrhotite to about 900° C (30). Considering the possible effect of small amounts of water and other constituents in addition to copper and nickel, the crystallization temperature of sulfides such as those at Pacific Nickel might be decreased to as low as 700° or 800° C. In any case a single pyrrhotite phase carrying nickel and some copper in solid solution would crystallize first and, if the amount of copper exceeded 2 percent, a residual copper-rich melt would form. This would crystallize as a separate copper-rich solid solution and then later exsolve as discussed earlier under mineralogy and texture. A residual copper-enriched melt could lubricate the ore during injection, eliminate deformative effects and form the minor cross-cutting veinlets and marginal copper enrichment that are locally common. However, any differential pressure on such a crystal mush might be expected to produce separate nickel- and copper-rich bodies by filter pressing.

Two main lines of objection to the magmatic injection theory are: (a) the zoned orebodies with their gradational contacts and undeformed silicates seem difficult to explain; (b) some of the sulfides must have been transported to produce the sulfide veinlets and impregnations with lower nickel content, the varied ore textures, the erratic copper mineralization at margins of orebodies, and the mineralization at contacts of various rock types. For explanation of these features, we must consider some type of hydrothermal replacement theory of origin as an alternative or addition to magmatic segregation and injection.

A Hydrothermal Theory

Although most hydrothermal ore-forming fluids cause alteration, and although ultrabasic rocks are especially easily hydrothermally altered, alteration at Pacific Nickel shows little relation to the main ore and is at least partly controlled by post-ore fractures. Most of the ore is fresh and the following evidence points to its origin at temperatures that exceed those of common hydrothermal alteration: (a) The ore was apparently formed before complete crystallization of the hornblende; as shown by textures, derivation of post-ore hornblendite dikes from the adjacent ultrabasics, and hornblendic reaction rims at contacts of the ore. (b) The sulfide exsolution textures indicate formation of the ore above 400° C. (c) Pyroxene hornfels inclusions indicate that temperatures above the 600° C range were attained at some time within the ultrabasics. (d) According to experiments by Bowen and Tuttle (4), water vapor could produce hydrous alteration in peridotite up to 800° C if saturated in silica, but only up to 650° C if lacking in silica. Thus 650° C would appear to be the minimum temperature for hydrothermal deposition of the sulfides in unaltered peridotite. Where alteration does locally accompany weak or dying phases of mineralization the hydrothermal fluid that produced it must have been below 650° C or else saturated in silica. Subsequent fluids in the post-ore stage were saturated in silica since they deposited quartz veinlets in alteration zones.

Bowen and Tuttle (4) also showed that above 650° C water vapor can convert enstatite to forsterite by removing silica and, by adding silica, it might convert forsterite to enstatite. They propose that such conversions could produce veinlike and pipelike bodies of olivine or orthopyroxene rock in ultrabasic complexes. Application of this reasoning to the veinlets and marginal zones of olivine and bronzite rock (locally mineralized) at Pacific Nickel strongly suggests that such vapors did traverse these ultrabasics. Perhaps the sulfide-rich pyroxenite and hornblendite "dikes" or "veins" were also formed by such vapors along fractures. Since some of the vapors formed olivine they were at least partly unsaturated in silica and thus their minimum temperature (without causing alteration) was indeed 650° C.

Now that it appears that such fluids probably were present and did carry some sulfides, the origin of the ore can be considered in this light. High-temperature, sulfide-bearing water vapor poor in silica thus might have formed the zoned pipelike orebodies, the olivine core being formed along a permeable channelway along which the vapor moved, while the orthopyroxene envelope was formed by vapor that had become enriched in silica removed from the core. This replacement-conversion process probably would have occurred in pyroxenitic host rock so lime would also have to be removed to convert any augite to olivine or orthopyroxene. Changing orthopyroxene to olivine or augite to orthopyroxene would increase the silica content of the proposed ore-forming fluid as shown by the following relations:

$$\underset{\text{(Orthopyroxene)}}{2(Mg,Fe)SiO_3} \rightarrow \underset{\text{(Olivine)}}{(Mg,Fe)_2SiO_4} + SiO_2$$

$$\underset{\text{(Augite)}}{Ca(Mg,Fe)Si_2O_6} \rightarrow \underset{\text{(Orthopyroxene)}}{(Mg,Fe)SiO_3} + SiO_2 + CaO$$

The zonal distribution of sulfides, their sequence of deposition, and their proportions of nickel and copper might be related somehow to this increase in silica or lime, or to decrease in pressure or temperature of the ore-forming fluid. This would explain the tendency for mineralization to occur near margins of peridotitic phases. Pyroxenitic cores within peridotite zones, as in the 512 orebody and at the portal of the 2600 level, might be explained by a resurgence of silica along the core. The ore-forming fluid, when expended in its ability to form olivine or to deposit major sulfide concentrations, may have redeposited its lime to form augite again, or to form the hornblendite bodies which resemble the sulfide bodies. The formation of hornblendite would require still further removal of silica from the pyroxenite. Some silica at this later stage may have been redeposited as talcose alteration which locally occurs near hornblendite and uralite zones and is common elsewhere in the ultrabasics:

$$3\ \underset{\text{(Orthopyroxene)}}{(Mg,Fe)SiO_3} + SiO_2 + H_2O \rightarrow \underset{\text{(Talc)}}{Mg_3(OH)_2Si_4O_{10}} + \text{magnetite}$$

At these later stages, mineralization would have occurred only where small amounts of sulfides (mostly pyrrhotite) were still locally carried; for example, in some of the hornblendite bodies and in altered fracture zones.

The above theory explains the zoned orebodies well; the massive ones might be considered as variations in spite of their differences (Pride of Emory and Brunswick No. 2 orebodies do show local pyroxenitic zones or shells). The large scale zoning from peridotite to pyroxenite and to hornblendite in the ultrabasic stock as a whole can be explained similarly by redistribution of silica, lime, etc., perhaps accompanied by some assimilative reaction at diorite and schist contacts, as suggested earlier. Such zoning was found in several of the smaller ultrabasic salients and also with weak mineralization at 1,370 feet on the 3550 level, and between Brunswick No. 8 and No. 9 orebodies.

In addition to the lateral concentric zoning observed at Pacific Nickel, a tendency for vertical axial zoning of the ore may also be expected from the replacement-conversion theory. As the proposed ore-forming fluid ascended, redistributing silica and lime and depositing sulfides, it might have tended to form the following upward succession of ores locally represented in chance sections by the various exposed orebodies: (a) low grade dunite high in proportion of nickel to copper (cores of Brunswick No. 5 and No. 6); (b) sulfide-rich dunite (Pride of Emory and 1600); (c) sulfide-rich harzburgite (Brunswick No. 1); (d) sulfide-rich bronzitite (Brunswick No. 2, No. 8 and No. 9); (e) erratically mineralized hornblendic bronzitite low in proportion of nickel to copper (1900). From further reasoning one might infer that the (e) type ore could terminate upward into barren hornblendite while some of the (a) type could terminate downward into barren dunite. Brunswick No. 1 and Pride of Emory orebodies do change from harzburgite and dunite to bronzitite between the 3550 level and the surface, but further evidence for vertical zoning is not yet apparent.

Under the replacement-conversion theory the deposits at Pacific Nickel might be genetically classified as pyrometasomatic. Like other pyrometasomatic deposits, which also show fresh euhedral silicates with sulfides, these

and other nickeliferous pyrrhotite deposits elsewhere in the world commonly are localized near contacts or pendants. The nickel deposits are even more closely associated both genetically and spatially with the parent intrusive than are other pyrometasomatic deposits, and more commonly occur within it rather than in its wall rocks, perhaps because of higher temperatures and because of physical conditions such as decreasing pressures and fracturing being more favorable in the cooling intrusive than in its wall rocks.

The chief objections to the above replacement-conversion theory of origin of ore at Pacific Nickel are the signs of movement suggestive of injection. These, it should be remembered, are as abundantly present in the hornblendite bodies which present similar problems but show even more evidence of replacement origin. Since the suggested temperatures of ore deposition at Pacific Nickel (mostly above 650° C) border on temperatures of partial melting of such sulfides (700 to 800° C), perhaps it may be possible for some flowage to occur in the most massively replaced localities, resulting in features suggestive of injection. On the other hand, injection of largely crystalline silicates and sulfides as proposed in the magmatic theory, accompanied to varying degrees by the replacement-conversion process, might account for massive and zoned ore almost as well. As seen from the genetic comparisons, many of the other nickeliferous pyrrhotite deposits, pipelike bodies, and zoned ultrabasics of the world are quite similar to those of Pacific Nickel and, although consensus of opinion on their origin tends to favor some type of replacement, evidence of movement or other features suggestive of flowage are left unexplained in some cases. The problems of physical state and of processes involved resemble those met in the origin of granite and pegmatite and the final answer on genesis of such ores may well involve both replacement and flowage. Nickeliferous pyrrhotite deposits should be well suited to further physical-chemical research on this problem of genesis because of their relative mineralogical simplicity and relative freedom from influence of external physical-chemical factors.

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SCIENTIFIC COMMUNICATIONS

A PROCEDURE FOR POLISHING ORE SECTIONS WITH DIAMOND ABRASIVE

EDWARD SAMPSON

In recent years great improvements have been made in the methods of polishing ore sections for microscopic study. For several years the writer has been using diamond abrasives. The resulting sections are of excellent quality and the method is so quick and simple that a short description may be of use. The method employs a diamond abrasive for the final polish. It does not require mounting most sections, although mounted sections can be readily polished. The method is fast and, in spite of using diamond for an abrasive, gives a very low unit cost for polishing.

The process has three stages: 1, rough grinding; 2, fine grinding; 3, polishing. Stage 1, rough grinding, is by normal methods. The sawn specimen is shaped and rough-ground by standard methods finishing with abrasive 600 carborundum and then AO abrasive 303½.[1] It is not necessary to mount the specimen in bakelite. Bakelite is used only for thin or fragile specimens and for concentrates. If a bakelite mount is used the edges of the mount should be beveled. Minor pits and cracks in the surface can be made harmless by applying a little Duco cement and then regrinding to remove the excess cement.

Stage 2, fine grinding, has already been described.[2] It has been found that groves in the laps are unnecessary. With careful use laps remain sufficiently true after years of use. Lap speeds of about 125–150 r.p.m. are satisfactory. Abrasive and oil mixtures are the same as previously described. Normally 2 minutes on the first lap and 1 minute on the second suffice. After this grinding the specimen should have a fine matte surface free from scratches.

Stage 3, polishing, presents new methods. The polishing is done on 7½-inch metal laps covered by silk bolting cloth. Polishing is in three stages, requiring three laps. The abrasives used are diamond powder which is available in a paste. The sizes used are, successively, 6 micron, 1 micron, and ¼ micron. The abrasive is supplied in a glass tube which fits into an applicator gun from which a thin ribbon of paste is extruded. About 1½ inch of this ribbon is taken on a finger tip and applied to the cloth in small spots, evenly distributed about the cloth. An oil lubricant is sprayed on while the

[1] Materials used are listed in a separate table.

[2] Sampson, Edward, A method for polishing sections of ores: Econ. Geol., vol. 44, p. 119–127, 1949.

lap rotates. The amount of lubricant should be just enough so that when the specimen is removed the face shows slight amount of oil. If the face of the section is free of oil the lap is too dry. With a little experience the operator can feel the conditions of the lap as polishing progresses and apply more lubricant when needed.

Normal lap speeds vary from about 350 to 800 r.p.m. This can be accomplished by a machine [3] having three spindles or by a single spindle machine with variable speed drive. In either case laps should be designed so that they are readily changeable. Where a three spindle arrangement is used speeds of about 350, 450, and 600 r.p.m. are satisfactory. Where a variable-speed control is used speeds of 800 r.p.m. or a little more may occasionally be used. The speed used depends on the nature of the material being polished.

The first stage of polishing is done with a lap speed of 450 r.p.m. and 6-micron abrasive. Moderately heavy pressure is applied and one minute usually suffices to take this stage to completion. It has been found that the above lap speed is about maximum advisable for the 6-micron abrasive. Also more lubricant is used for this stage than for the subsequent ones. The section is rotated every 15 seconds.

The second stage is commonly done at the same lap speed. One minute will usually give a nearly perfect polish to pyrite. Some minerals, for example, magnetite, may polish better with higher speed and high pressure.

The final polish is done with ¼-micron abrasive. Here the lap speed and pressure will vary according to the mineral assemblages. Moderate speed and pressure will give an excellent polish to pyrite. Soft minerals can be polished better at low speed and light pressure. Some minerals, such as magnetite or pitchblende, require high speed and very high pressure. A limiting factor in this case is heating of the specimen. A speed of 850 and strong hand pressure will warm a thin section in 10 to 15 seconds too hot for comfortable handling and in this case the section must be cooled by taking it from the lap and running water over it. However, this procedure has given some excellent results on difficult sections.

The cost of polishing materials for a period of several months use averaged 4.4 cents per section on the basis of one minute per section on each lap.[4]

MATERIALS AND APPROXIMATE PRICES

Cloth—Abbe Engineering Co., Hudson Terminal Bldg., 50 Church St., New York.

Tetcosilk 12xx Bolting cloth, 125 mesh, 40 inches wide. This is bought in 90-inch lengths and yields 36, 10-inch squares. Price for 90 inches $16.50

[3] A three spindle machine was made by the S. G. Frantz Co., Kline Ave., Trenton, New Jersey. Those having these machines can adapt the drive pulleys to give appropriate speeds. Laps to hold the silk cloth can be secured from the Frantz Co. This company is in process of designing a single-spindle machine with variable speed drive. The laps are readily interchangeable and it should be possible to use a single unit for both iron laps for fine grinding and cloth-covered laps for polishing.

[4] Unit costs per minute of use: cloth .91 and abrasive .54 cents.

Abrasives, etc.—Buehler Ltd., 2120 Greenwood St., Evanston, Illinois.

Catalog No.		
1544 AB	Diamet-Hyprez polishing compound Grade 000, 0–½ micron [Ave. ¼ micron]. 5 grams with applicator gun	17.50
1544 R AB	Refill tubes. 5 gram	15.50
1546 AB	Same—grade 00, 0–2 micron. [Ave. 1 micron]	10.00
1546 R AB	Refill tubes. 5 gram	8.00
1548 AB	Same—grade 1, 4–8 micron. [Ave. 6 micron]	21.00
1548 R AB	Refill tubes	19.00
1542 AB	Diamet-Hyprez fluid, with atomizer applicator	2.50
1942 R AB	Diamet-Hyprez fluid 4 oz. bottle	1.00

American Optical Company, Buffalo, New York

Abrasive No. 303½, per pound about	.75
Abrasive No. 305, per pound about	.75

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REVIEWS

India's Mineral Wealth. By J. Coggin Brown and A. K. Dey. Third ed. with Dey as co-author for present ed.; p. 761; maps 12; pls. 8; graphs 24; tbls. 136. Oxford University Press, Bombay, 1955. Price, Rs. 30.

Coggin Brown's earlier editions of *India's Mineral Wealth* are only too familiar to students of Indian mineral deposits to need an introduction here. The present volume is a revised and considerably enlarged third edition with the co-authorship of Dr. A. K. Dey, who, as Superintending Geologist of the Geological Survey of India, is thoroughly conversant with the trends in present-day exploration and exploitation of the mineral resources of India. In addition to their own personal experience and familiarity with the subject, the authors have consulted several specialists in the various fields to make the information as authoritative and accurate as possible.

At first glance, the book is very impressive with an almost two-fold increase in the number of pages over the previous edition. The major arrangement of topics has remained the same in essence, though with considerable expansion of detail and addition of data. By far the most welcome addition is Part V of the book, with the two chapters on Water Supplies and Soils. With the launching of the vigorous plans of economic development and food production by the governments of India, Pakistan and Burma, a study of these two types of resources has gained new importance and it is to the authors' credit that proper place be given these resources in a book of this sort. Another important addition is the chapter on the atomic mineral resources, which, of late, have assumed tremendous importance in the mineral resources of any country.

The book is divided into five parts and at the beginning a geologic map of the Indian subcontinent is provided, showing the distribution of the major rock types in Pakistan, India and Burma.

Significantly enough, the first part deals with the mineral fuels, coal and oil. The subheadings are based on the geographical distribution of the fuels in the three countries. At the outset, a brief summary of the early history is given to facilitate a background understanding of the development of the industry. Excellent maps and tables provide the vital information as to the location, extent and grades of fuels available. Each coal field is described concisely with the approximate analyses of various important types of coal produced. The oil fields of Pakistan, India and Burma are described at length along with the stratigraphy of Cenozoic (Tertiary) rocks. A brief account of the individual oil fields of the three countries is included with authentic information furnished by the geologists of the leading oil companies operating in the area. At the end of Part I are exhaustive tables listing production figures, costs, imports and exports, while graphs show the production trends of various coal and oil fields, with their total output of the last fifty years.

Part II of the book deals with the various metal resources. They are subdivided mainly on the basis of their uses, such as ferrous, steel-hardening alloys, precious and atomic metals. Each chapter deals with the occurrence, general geologic set-

ting, production and reserves of the individual groups of metals. In recent years, reserves of iron and manganese ores of India have multiplied several-fold due to modern techniques of exploration, and India has assumed the role of a great potential supplier of these ores. These two metals have been discussed exhaustively and brief mention is made of the various theories of their origin. One apparent thing, both in the section on metals and their ores, as well as in the following sections, is the significant increase in the number of individual minerals included. For example, under Part II in the second edition, are listed about twenty-one metals, whereas in the present edition about forty-three metals are included. With industrial progress and improved technology, more and more mineral resources will be consumed, and this trend is clearly shown in this volume by the increased number of metals and other mineral resources produced by the three countries.

Part III of the book includes raw materials used in engineering, construction, agriculture, refractories, etc. Materials included in this section have risen in importance in the wake of economic development plans introduced by the governments of these countries. The occurrence, analysis of important materials, production and reserves are given in a very clear manner.

Part IV deals with the occurrence of various precious and semiprecious gem stones in India, Pakistan and Burma. India has been known for its diamonds and rubies since early history, but the industry faded away completely in modern times. In recent years, efforts have been made to revive the industry and some progress has been registered in this direction. In addition to diamonds, rubies of Burma, sapphires of Kashmir and various other gem stones are dealt with in this section. This part is divided into three chapters, Precious Stones, Uncommon Gem Stones, and Semiprecious and Decorative Stones, under which are included minerals like chalcedonic quartz, jadetite, lapis lazuli, etc.

Part V is the new addition to this volume and deals with water supplies and soils. At the beginning of the section is a generalized geological and meteorological map of India, Pakistan and Burma showing various climatic zones of the three countries. The annual precipitation varies between extremes in different parts of the Indian subcontinent. Water supply, both for domestic consumption and for irrigation, has been a major headache in many parts of the country. A wise appraisal and careful utilization of the ground water resources is in order. In the first chapter the ground water conditions obtaining in the various groups of rock formations, their mode of occurrence, and the methods adopted for recovery in various parts of the country are given. Brief mention is also made of the various development programs now in operation to utilize the ground water in the Indo-Gangetic alluvium, important hydroelectric and surface water projects of the three countries. The second chapter in this section deals with soil resources. The soils have been divided into three groups, the mature soils of peninsular India, the alluvial soils of the Indo-Gengetic Plain, and the ill developed scanty soils of mountainous parts of extra-peninsular India. Under each group, the various types of soils, their source rocks and origin have been discussed. A soil map of India, Pakistan and Burma show the distribution of the various types of soils.

The appendix at the end of the volume gives some of the very recent production data. A good bibliography is provided for any one interested in delving into the extensive and diffused literature on the various topics. A well prepared index makes reference to any topic in the book easy.

With the achievement of independence, India, Pakistan and Burma have taken on a new approach of intensive internal exploration and exploitation of their mineral resources. This present edition of *India's Mineral Wealth*, by Brown and Dey, very ably and with a comprehensiveness commensurate with conciseness, sums

up the trends of development in the mineral resources of these countries from the beginning of the present century.

The authors' claim that the main object of the book is "to draw attention to the commercial and industrial potentialities which the mineral deposits of these three countries possess" appears very modest indeed. The authors have done an excellent job of compilation and collection of information from miscellaneous and rather obscure publications and have brought out an up-to-date and authentic source book of information on the mineral deposits of India, Pakistan and Burma. There is no doubt that the book will be very useful as a reference work on Indian mineral deposits, and will succeed in drawing the attention of a large public to the great mineral potentialities of India, Pakistan and Burma.

V. RAMA MURTHY

YALE UNIVERSITY,
NEW HAVEN, CONN.,
May 17, 1956

La Genèse des Sols en tant que Phénomène Géologique. (Soil Genesis as a Geologic Phenomenon.) By H. ERHART. Pp. 90. Masson et Cie, Paris, 1956. Price, 560 fr.

The progress of pedology, the science of soil genesis, and its contributions to other fields such as ecology, phytosociology, and phytogeography are by this time well known. Certainly, no mention need even be made of the importance of this science to agronomy, which has profited greatly from the advances made in pedology. M. Erhart, author of the first treatise in French on pedology which appeared in 1935, discloses in this, his latest book, a new aspect of this science. Soil genesis is revealed as a geologic phenomenon equal, if not superior, in importance to other natural phenomena such as glaciation, volcanism, erosion, etc., and knowledge of this phenomenon throws new light on many fundamental geologic problems.

This original synthesis is the result of years of careful observation and scientific exploration, coupled with a thorough knowledge of physical chemistry, mineralogy, geology and geochemistry. One of the most challenging ideas in this work is the discussion of biological equilibrium and disequilibrium. Although this is as yet an embryonic theory, it is already possible to foresee certain deductions that are bound to make their impression on modern geologic thought.

Soil Genesis as a Geologic Phenomenon is a highly condensed work, well organized and written with great clarity of style. It is divided into five chapters: Basis and Definition of the Biorhexistatic Theory (biological equilibrium and disequilibrium); Soil and Sediment Genesis; Discussion of the Problems of Chronology and Causes in Geology; Discussion Pertaining to Continental Sediments; Evolution of Mineral Matter and Biological Transformism.

The interest of this book is in no way limited to geologists. All natural scientists will be stimulated by the ideas that have evolved from this new stage in the development of the science of pedology.

B. A. BROMBERT

NEW HAVEN, CONN.

Microscopic Petrography. By E. WM. HEINRICH. Pp. 296; figs. 70. McGraw-Hill Book Co. New York, 1956. Price $6.50.

This much needed book is intended to serve as a text on the initial and intermediate level of the microscopic study of rocks. It is planned for students of geology and for practicing geologists in the field of mineral industries and mining.

It presupposed that the reader is familiar with the optical properties of the more common rock-forming and accessory minerals.

The first chapter deals with the methods of microscopic study. The following chapters, in pairs, take up the general features and descriptions of the igneous, sedimentary and metamorphic rocks, followed by a bibliography. One learns of the special features and the textures of each of the groups of rocks, and interpretations of their genesis based upon these features. The book also includes up-to-date material such as the use of the pointer counter, insoluble residues, heavy detrital minerals, and evaporates.

The book is well printed on a glossy paper that brings out clearly the many microphotographs of rocks. It is a book that should prove very helpful to all students of petrography.

Rocks and Minerals. By RICHARD M. PEARL. Pp. 275; pls. 12; figs. 35. Barnes & Noble, Inc., New York, 1956. Price, $1.95.

This little paper-covered book covers, in 260 pages, a popular discussion of rocks and minerals. The author, well known as a popular scientific writer, covers recent knowledge about the mineral kingdom. The subject matter includes rocks and minerals, ores and metals, crystals, gems and meteorites, and follows them through from their origin and occurrence to their industrial uses. It takes up classification, identification, collection, prospecting and mining. The text matter is divided into 17 chapters, many of which have enticing titles such as The Realm of Gems, Minerals That Glow in the Dark, Stones from the Sky, or Oddities of the Mineral Kingdom (asbestos, flexible sandstone, etc.).

Although written in popular language, the subject matter is scientifically accurate. The writing is clear and concise and catchy phrases intrigue the reader. There are many illustrations, among which twelve colored plates of ores and minerals. The book is one in which amateur mineral collectors will revel and should serve as a useful textbook for secondary schools that teach earth sciences.

Die Bergwirtschaft der Erde. By FERDINAND FRIEDENSBURG. Pp. 562; figs. 49. Ferdinand Enke Verlag, Stuttgart, 1956. Price, DM 69.

This monumental compilation assesses the mineral production of 154 separate countries or colonies. After a brief introduction, the author starts in with Aden and considers each country alphabetically through to Vereinigte Staaten von Amerika (United States) devoting a page or a few pages to each. Under each country is given a table of the production of each mineral for 1913, 1939 and 1950 to 1954, and the percentage of world production. For many countries there are also maps showing the location of the important deposits of each metal or mineral. The text matter for each country gives the new developments in mineral discoveries, mining and technology, the chief deposits of each metal or mineral, the outlook and a few words about the potential situation. After each country there follow references on the important minerals, mines and mineral resources. The last section of the book contains a series of useful tables of the chief metals and minerals with world and country production of each for the years 1945 to 1954, with 1954 incomplete.

The volume contains a vast amount of mineral resources information and is a handy reference to the occurrence and production of minerals in each country. An excellent index of subject and place permits quick reference to desired material.

United States and Canada, Second Edition. By ALFRED J. WRIGHT. Pp. 590; figs. 207. Appleton-Century-Crofts, Inc., New York, 1956. Price, $7.00.

This second edition of a regional geography text and reference is a very thorough revision with text rewriting, and very many new maps, charts, and illustrations. It is presented in three parts. Part I covers general economic activities dealing with agriculture, minerals, manufacturing and commerce. Part II considers the geographic regions of continental United States giving for each the geography, climate, soils, population, forests, fishing, agriculture, mining, manufacturing, industries, and a bibliography. There are many tables and profuse illustrations, most of which are of excellent quality. Part III, deals with Canada, Alaska and Hawaiian Islands. In Part IV, the author, under "Prospect," considers briefly future changes that may occur in the economic life of these countries.

In its revised form, the book is a good text and a handy reference on these countries.

Die Entwicklungsgeschichte der Erde. Pp. 652; figs. 184; tbls. 45. Veb F. A. Brockhaus Verlag, Leipzig, 1955.

Here is a rather unusual book on elementary geology, unusual in that the various parts are contributed by different authors. The first section is on physical geology with consideration of the earth's crust, magmatic process and rocks, sedimentary processes and rocks, metamorphic processes, the work of wind and water, structure and geotechtonics, totaling 218 pages. Historical geology is treated in the customary chronological order in 238 pages. The chief value of the book lies in a rather thorough glossary—really a dictionary—of geologic terms occupying 175 pages of very fine print.

The book as a whole is quite unpleasing in that the style is nonuniform, it is printed in very fine footnote type, difficult to read and the illustrations are poor.

BOOKS RECEIVED

KURT SERVOS

The Descent of Pierre Saint-Martin. NORBERT CASTERET. Pp. 160; pls. 24. Philosophical Library, New York, 1956. Price, $4.75. *Thrilling account, translated from the French by John Warrington, of the exploration of the cavern of Pierre Saint-Martin, 2,389 ft. deep, second deepest cavern in the world.*

Bulletin Scientifique et Economique, No. 3, December, 1955. Pp. 140. Bureau de Recherches Minières de l'Algérie, Alger, 1956. *Seven papers deal with Algerian geology.*

Mineral Resources Navajo-Hopi Indian Reservations, Arizona-Utah, Vol. II, Nonmetallic Minerals. Pp. 106; figs. 28; tbls. 12. Bureau of Indian Affairs, University of Arizona, Tucson, 1955. *The nonfuel nonmetallic mineral resources in this area of 25,000 sq. mi. include limestone, clay minerals, pozzolan, gypsum, coal and semiprecious gemstones.*

Pub. Dominion Observatory, Vol. XIV, Bibliography of Seismology, No. 15. Pp. 313–336. Canada Dept. of Mines, Ottawa, 1956. Price, 25 cts.

Bulletin des Séances, II–1. Pp. 121. Académie Royale des Sciences Coloniales, Bruxelles, 1956. Price, *F* 100. *This new series constitutes the successor to the* Bulletin des Séances *published by the Institut Royal Colonial Belge from 1929 to 1954.*

Report of the Director, 1954–55. Pp. 14; pls. 2. Gold Coast Geol. Survey, Accra, 1956. Price, 2 *s.*

Determinação Espectroquímica de maiores e menores constituintes, em pequenas amostras de Minerais. C. V. DUTRA. Pp. 8; tbls. 8. Instituto de Pesquisas Radioativas, Belo Horizonte, 1955.

Subsurface Geology of the Mississippi Embayment of Southeast Missouri. J. G. GROHSKOPF. Pp. 133; pls. 9; figs. 3; tbls. 7. Missouri Geol. Survey, Vol. XXXVII, Second Ser., Rolla, 1955.

Records of the Geological Survey, Year ending 31st December, 1954. Pp. 19. Geol. Survey of Northern Rhodesia, Lusaka, 1956. Price, *2 s, 6 d.*

First Annual Report Ontario Fuel Board, 1954. Pp. 137; figs. 9; tbls. 19. Ontario Dept. of Mines, Toronto, 1955.

Die Fauna der Leimitz-Schiefer (Tremadoc). KLAUS SDZUY. Pp. 74; figs. 48; pls. 8. Abh. Senckenbergische Naturforschende Gesellschaft, 492, Frankfurt am Main, 1955.

The Geology and Archeology of the Little Caledon River Valley, Pt. I: Geology, D. J. L. VISSER; **Pt. II: Archeology,** C. VAN RIET LOWE. Pp. 64; pls. 8; figs. 11. Dept. of Mines, Union of South Africa, Pretoria, 1955. Price, 5 *s*.

Bureau of Mineral Resources, Geology and Geophysics—Canberra, 1954.

Rept. No. 8. Geological and Geophysical Surveys, Ashford Coal Field, New South Wales, Pt. I—Geology, H. B. OWEN and G. M. BURTON; **Pt. 2, Geophysical Survey,** L. W. WILLIAMS. Pp. 66; pls. 9. *Indicated reserves amount to 4.9 million long tons of coal in rocks of early Permian age.*

Rept. No. 11. The Nelson Bore, South-Western Victoria, Micro-Paleontology and Stratigraphical Succession. I. CRESPIN. Pp. 39; pls. 2.

Illinois Geological Survey—Urbana, 1956.

Circ. 208. Illinois Oil Shales. J. E. LAMAR, W. J. ARMON and J. A. SIMON. Pp. 21; figs. 2; tbls. 6. *Investigation indicates that the oil shales are more likely to have future significance than their present commercial importance.*

Circ. 209. Unpublished Reports on Open File, II. Industrial Minerals. M. B. BROPHY. Pp. 8.

Rept. of Inv. 193. Subsurface Geology and Coal Resources of the Pennsylvanian System in Crawford and Lawrence Counties, Illinois. P. E. POTTER. Pp. 17; pls. 4; figs. 5; tbl. 1. *Total coal reserves are estimated at more than 5.3 billion tons.*

Geological Survey of Japan—Hisamoto-cho, Kawasaki-shi, 1956.

Explanatory Text of the Geological Map of Japan. Ube Tobu (Fukuoka-36). MICHIYA KOUNO. Pp. 25. *Important coal seams, some extending and being mined beneath the sea, provide the principal economic resource. Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Shuzenji (Tokyo-100). KONOSUKE SAWAMURA. Pp. 51. *Gold is the most important mineral commodity; four mines are producing it. Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Ohazama (Akita-38). OSAMU HIROKAWA and TAKASHI YOSHIDA. Pp. 40. *Gold, molybdenum, titaniferous magnetite, talc, quartz, limestone and marble comprise the relatively unimportant economic mineral deposits. Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Kofu (Tokyo-59). MASATO KATADA. Pp. 31. *Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Aniai (Akita-4). MASATSUGU SAITO and ATSUSHI OZAWA. Pp. 48. *Fissure-filling veins contain copper and associated metals (1954 production was 4,200 tons of copper concentrate with 16.8% Cu and 1.2 g/t Au). One of the mines has been continuously productive since 1575. The area also yields coal. Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Abuta (Sapporo-50). RYOHEI OTA. Pp. 84. *Limonite ore, extending downward into a marcasite deposit, has been extracted for many years. Text in Japanese, résumé in English. Geologic map 1:50,000.*

Geological Survey of Kansas—Lawrence, 1956.

Bull. 113. Gypsum in Kansas. R. O. KULSTAD, PAUL FAIRCHILD and DUNCAN MCGREGOR. Pp. 110; pls. 20; figs. 15; tbls. 2. *The known gypsum deposits occur in rocks of Permian age.*

Bull. 118. Stratigraphy of the Ogallala Formation (Neogene) of Northern Kansas. J. C. FRYE, A. B. LEONARD and ADA SWINEFORD. Pp. 92; pls. 9; figs. 5.

North Dakota Geological Survey—Grand Forks, 1956.

Circ. 5. Data for 1,125 Wells Drilled in North Dakota. Pp. 157.

Geologic Map of North Dakota. MILLER HANSEN. 1 sheet.

Quebec Department of Mines—Quebec, 1956.

Preliminary Rept. 323. Blaiklock Area, Abitibi Territory and Abitibi-East County. R.-J.-E. SABOURIN. Pp. 6. *Geologic map, 1:62,500.*

Preliminary Rept. 324. Mule Lake Area, Saguenay County. W. B. EMO. Pp. 7. *Geologic map, 1:62,500.*

Preliminary Rept. 325. Leopard Lake Area (East Half), New Quebec. PIERRE SAUVÉ. Pp. 6. *The area contains sulfide mineralization. Geologic map, 1:62,500.*

Bureau of Economic Geology—Austin, Texas, 1956.

Pub. 5605. Basement Rocks of Texas and Southeast New Mexico. P. T. FLAWN. Pp. 261; pls. 10; figs. 2; tbls. 12. Price, $2.50. *Study of core and cuttings from 760 wells leads to a division of the Precambrian basement into seven major lithologic and litholigic-structural units. Three appendices add to the usefulness of this monograph.*

Pub. 5607. Geology of the Late Paleozoic Horseshoe Atoll in West Texas. D. A. MYERS, P. T. STAFFORD and R. J. BURNSIDE. Pp. 113; pls. 18; figs. 10; tbls. 10.

U. S. Atomic Energy Commission—Oak Ridge, Tenn., 1955–56.

RME-3110 (Pt. III). Annual Report for June 30, 1954 to April 1, 1955. Part III. Collapse Features, Temple Mountain, Uranium Area, Utah. P. F. KERR, D. R. KELLEY, W. S. KEYS and M. W. BODINE, JR. Pp. 138; pls. 13; figs. 33; tbls. 8. Price, 70 cts. *Uranium mineralization seems to postdate the collapse features.*

NYO-3936. Variations in Isotopic Abundances of Strontium, Calcium, and Argon and Related Topics. Pp. 69. *Isotope studies lead to many new age determinations and, in some cases, act as internal checks.*

U. S. Geological Survey—Washington, D. C., 1956.

Bull. 656-D. Birth and Development of Parícutin Volcano, Mexico. WM. F. FOSHAG and JENARO GONZALEZ R. Pp. 355–389; pls. 40; figs. 16; tbls. 3. *The lavas of Parícutin, during the first 2½ years of its life, were andesite-basalt.*

Bull. 975-E. Geology and Ore Deposits of the Atacocha District, Departamento de Pasco, Peru. R. F. JOHNSON, R. W. LEWIS, JR., and G. ABELE C. Pp. 337–388; pls. 8; figs. 8. Price, $2.00. *Since 1940 more than 90,000 t Pb and 65,000 t Zn, with Ag as an important byproduct, have been produced.*

Bull. 1009-K. Uranium-Bearing Nickel-Cobalt-Native Silver Deposits, Black Hawk District, Grant County, New Meico. ELLIOT GILLERMAN and D. H. WHITEBREAD. Pp. 283–313; pls. 3; figs. 5; tbls. 3. Price, 65 cts. *The ore deposits are similar to the ones at Great Bear Lake and at Joachimsthal.*

Bull. 1009-L. Radioactive Deposits in New Mexico. T. G. LOVERING. Pp. 315–390; pls. 7; figs. 9; tbls. 12. Price, 70 cts. *Forty-five areas of radioactivity were known prior to 1952.*

Bull. 1021-E. Geology of Comb Ridge and Vicinity North of San Juan River, San Juan County, Utah. J. D. SEARS. Pp. 167–207; pls. 4; figs. 2. Price, 75 cts.

Bull. 1026. Geology of the Bighorn Canyon-Hardin Area, Montana and Wyoming. P. W. RICHARDS. Pp. 93; pls. 7; figs. 8; tbls. 4. *Mineral deposits include bentonite, gypsum, limestone, and some oil and gas. Geologic map, 1:62,500.*

Bull. 1027-I. Perlite Resources of the United States. M. C. JASTER. Pp. 375–403; pl. 1; tbl. 1.

Bull. 1033-D. Geophysical Abstracts October–December, 1955. M. C. RABBITT, D. B. VITALIANO, S. T. VESSELOWSKY, and others. Pp. 211–340. Price, 25 cts.

Prof. Paper. 273. Geology and Mineral Deposits of the Boleo Copper District, Baja California, Mexico. I. F. WILSON, in collaboration with V. S. ROCHA. Pp. 134; pls. 11; figs. 38; tbls. 33. *Ore grade has ranged from more than 8% to 3.5% Cu (1886–1947 average, 4.8%) in this second largest copper producing district in Mexico. Origin suggested for the deposit is replacement of favorable beds by hydrothermal solutions.*

Prof. Paper 282-A. Ephemeral Streams—Hydraulic Factors and Their Relation to the Drainage Net. L. B. LEOPOLD and J. P. MILLER. Pp. 37; figs. 27. Price, 45 cts.

Water-Supply Paper 1355. Geology and Ground-Water Resources of the Lower Yellowstone River Valley, Between Glendive and Sidney, Montana. A. E. TORREY and F. A. KOHOUT. Pp. 92; pls. 2; figs. 14; tbls. 4. Price, $1.00. *Geologic map, 1:125,000.*

SCIENTIFIC NOTES AND NEWS

J. E. WHIMSTER, of the Department of Industrial Development, Canadian Pacific Railway Company, has been transferred from Montreal to Toronto as Industrial Geologist.

H. D. M. JAGER, formerly chief engineer for Bralorne Mines, Ltd., has been appointed chief engineer for Pioneer Gold Mines of B. C., Ltd.

R. W. SPENCE, is now field engineer for O'Brien Gold Mines, Ltd., Cadillac, Que. Previously, for seven years, he had held a similar position with the Mining Corporation of Canada, Ltd.

W. W. WIERZBICKI is now geologist in charge for C.D.C. Coal Investigation, Tukuyo, Tanganyika, East Africa.

L. ALBERTO J. TERRONES, formerly Assistant Chief Geologist for the Cerro de Pasco Corp., is now on the geological staff of the Cananea Consolidated Copper Company, Mexican subsidiary of the Anaconda Company, in the capacity of exploration geologist in charge of the Exploration Department at Mexico City.

GABOR DESSAU, "Chargé de Cours" of Mineral Deposits at the University of Naples and, since its inception, in charge of the Uranium Prospecting Centre of the ANI–AGIP group has been attached, for a period of two years, to the "Technion" (Israel Institute of Technology) in Haifa as UNESCO expert to advise on the setting up of a Geological Engineering and Mineral Sciences Department.

W. JAMES BICHAN, is on long leave after two and a half years in charge of exploration in Northern Rhodesia for Mineral Search of Africa, Ltd., subsidiary of Rio Tinto Exploration and Finance, Ltd., of London, England.

FREDERICK H. LAHEE, petroleum geologist, announces the opening of his office at 7219 Kenny Lane, Dallas 30, Texas.

WILLIAM C. SCHMIDT and NEIL A. O'DONNELL announce the opening of their office as mining consultants under the firm name of O'Donnell and Schmidt at 165 Broadway, New York 6, N. Y.

THE UNIVERSITY OF NEW MEXICO, GEOLOGICAL DEPARTMENT, played host in its new building to the annual meeting of the Rocky Mountain Section of the Geological Society of America on May 3–5, when a total of 40 papers were presented and a field trip was held attended by 100 people. The total attendance was more than 300 people, including wives. G.S.A. Fellows and Members numbered 127.

JON L. RAU has received the STANOLIND FOUNDATION FELLOWSHIP IN GEOLOGY at Yale University for the 1956–57 academic year. Stanolind Foundation, Inc., was created and is supported by the Stanolind Oil and Gas Company. The fellowship in geology carries a stipend of $1,500 for the year, covers cost of tuition and fees, and provides an additional $500 for extra work.

ROBERT H. LYDDAN has been appointed as assistant director of the Geological Survey. He has been regional engineer at the Atlantic regional office, topographic division, Arlington, since July 1955. Prior to that date he served as chief of the division's plans and coordination branch since 1947.

THE WYOMING GEOLOGICAL ASSOCIATION will hold its Eleventh Annual Field Conference on September 5, 6, 7, 1956; registration will start Sept. 4. Headquarters will be at the Jackson Lake Lodge in Moran, Wyoming, and daily field trips will be conducted throughout the Jackson Hole area. The first day's trip will include a ride up the ski lift on Snow King Mountain to view the general tectonics of the Jackson Hole area. The afternoon will be spent inspecting Early and Late Tertiary Thrusting on the southwest flank of the Gros Ventre Mountains. The second days will be spent along the Gros Ventre River up to Sohare Creek to study structural and stratigraphic conditions. The last trip will be from Moran through Togwotee Pass with additional road logs provided for unscheduled continuance to Dubois or Lander. Information concerning reservations should be directed to K. W. Frielinghausen, Box 1571, Casper, Wyoming.

WILLIAM BELLANO has been named to the newly created post of director of mining and minerals exploration for International Minerals & Chemical Corp.

C. A. LEHNERTZ, JR., former resident geologist for Colorado Exploration Co., Lander, Wyo., for the past two years, has joined the staff of Doeringsfeld, Amuedo and Ivey, specialists in photogeologic evaluations, in Denver.

GROVER C. DILLMAN, president of the Michigan College of Mining & Technology, will retire from his position on October 1, 1956.

F. H. STEWART, vice president and general manager of the Southwest Potash Corp. (a subsidiary of the American Metal Co.) Carlsbad, N. M., has been appointed manager, Mining and Exploration Dept., The American Metal Co., with headquarters in New York.

CHARLES K. LEITH received a citation for outstanding services from the AEC on April 17, 1956, on his retirement as a member of the Combined Development Agency. The latter, is a joint U. K.–U. S.–Canadian organization established in 1944 in Washington to procure and develop the production of uranium and thorium supplies in such areas as the Belgian Congo, Australia, and Portugal. Dr. Leith has been one of the three U. S. representatives on the agency since its establishment.

J. O. K. KALLIOKOSKI has been appointed Assistant Professor of Geology at Princeton University beginning in September. He is currently associated with the Newmont Mining Company in Arizona and was formerly a member of the Canadian Geological Survey. At Princeton he will devote his time to the general subject of mineral deposits.

ALLAN F. MATTHEWS, economic geologist for the U. S. International Cooperation Administration, has been transferred from Washington, D. C., to Bonn, Germany. He is program officer for U. S. aid, now largely limited to Berlin.

HOWARD W. MILLER has been appointed superintendent, zinc mining operations, The New Jersey Zinz Co., Jefferson City, Tenn. Mr. Miller joined the company in 1946 as a geologist, exploration unit, Austinville, Virginia mine. He was transferred to Jefferson City in 1949.

MATTHEW P. NACKOWSKI has resigned as associate professor of geology, geology department, Missouri School of Mines, Rolla. Mr. Nackowski has accepted an appointment as associate professor of mining geology, Department of Mining and Geological Engineering, University of Utah, Salt Lake City.

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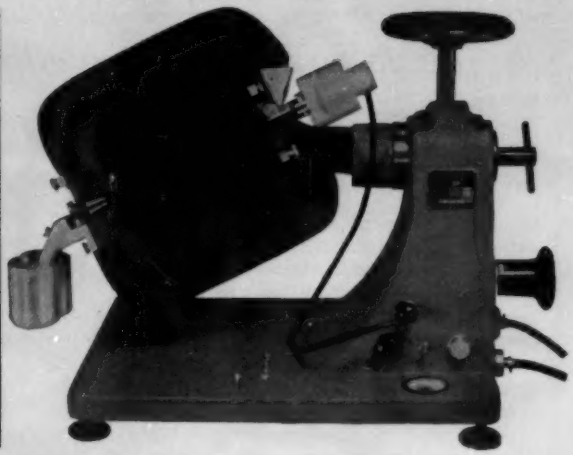

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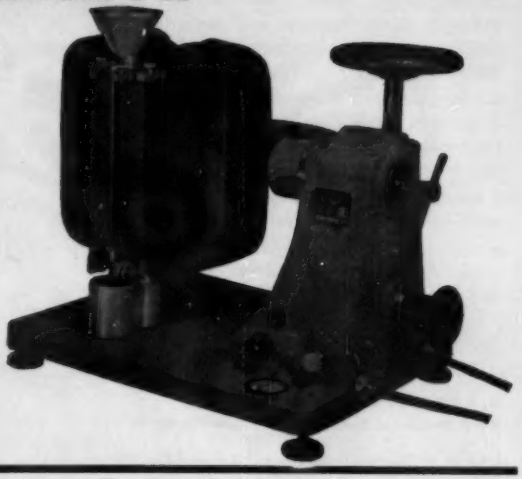

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